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ABSTRACT

Nuclear physics fundamentals are presented in this sixth unit of the Project Physics text for use by senior high students. Included are discussions of radioactivity, taking into account Bacquerel's discovery, radioactive elements, properties of radiations, radioactive transformations, decay series, and half-lives. Isotopes are analyzed in connection with positive rays, mass spectrographs, notations for nuclides and nuclear reactions, relative abundances, and atomic masses. Nuclear structures and reactions are studied by using proton-electron and proton-neutron hypotheses with a background of discoveries of neutrons, neutrinos as well as artificial transmutation and artificially induced radioactivity. Information about binding energy, mass-energy balance, nuclear fission and fusion, stellar nuclear reactions, nuclear force and model, and biological and medical application of radioisotopes is given to conclude the whole text. Historical developments are stressed in the overall explanation. Problems with their answers are provided in two categories: study guide and end of section questions. Besides illustrations for explanation use, charts of elementary particles and physical constants with conversion factors are also included in this text unit as appendices. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

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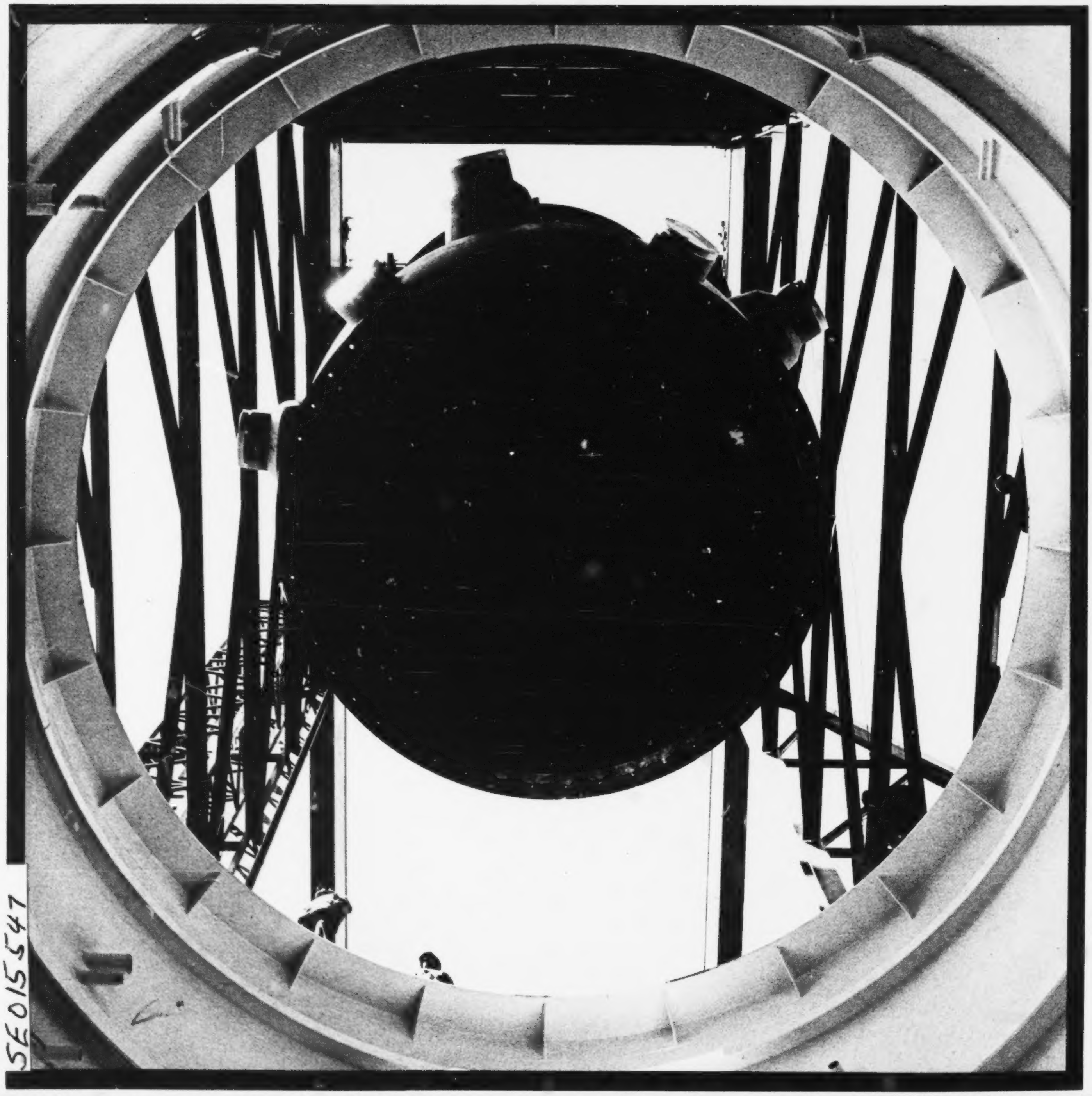
Project Physics **Text** 6

An Introduction to Physics

The Nucleus



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Project Physics **Text**

An Introduction to Physics 6 The Nucleus

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Welcome to the study of physics. This volume, more of a student's guide than a text of the usual kind, is part of a whole group of materials that includes a student handbook, laboratory equipment, films, programmed instruction, readers, transparencies, and so forth. Harvard Project Physics has designed the materials to work together. They have all been tested in classes that supplied results to the Project for use in revisions of earlier versions.

The Project Physics course is the work of about 200 scientists, scholars, and teachers from all parts of the country, responding to a call by the National Science Foundation in 1963 to prepare a new introductory physics course for nationwide use. Harvard Project Physics was established in 1964, on the basis of a two-year feasibility study supported by the Carnegie Corporation. On the previous pages are the names of our colleagues who helped during the last six years in what became an extensive national curriculum development program. Some of them worked on a full-time basis for several years; others were part-time or occasional consultants, contributing to some aspect of the whole course; but all were valued and dedicated collaborators who richly earned the gratitude of everyone who cares about science and the improvement of science teaching.

Harvard Project Physics has received financial support from the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education and Harvard University. In addition, the Project has had the essential support of several hundred participating schools throughout the United States and Canada, who used and tested the course as it went through several successive annual revisions.

The last and largest cycle of testing of all materials is now completed; the final version of the Project Physics course will be published in 1970 by Holt, Rinehart and Winston, Inc., and will incorporate the final revisions and improvements as necessary. To this end we invite our students and instructors to write to us if in practice they too discern ways of improving the course materials.

The Directors
Harvard Project Physics

An Introduction to Physics 6 The Nucleus

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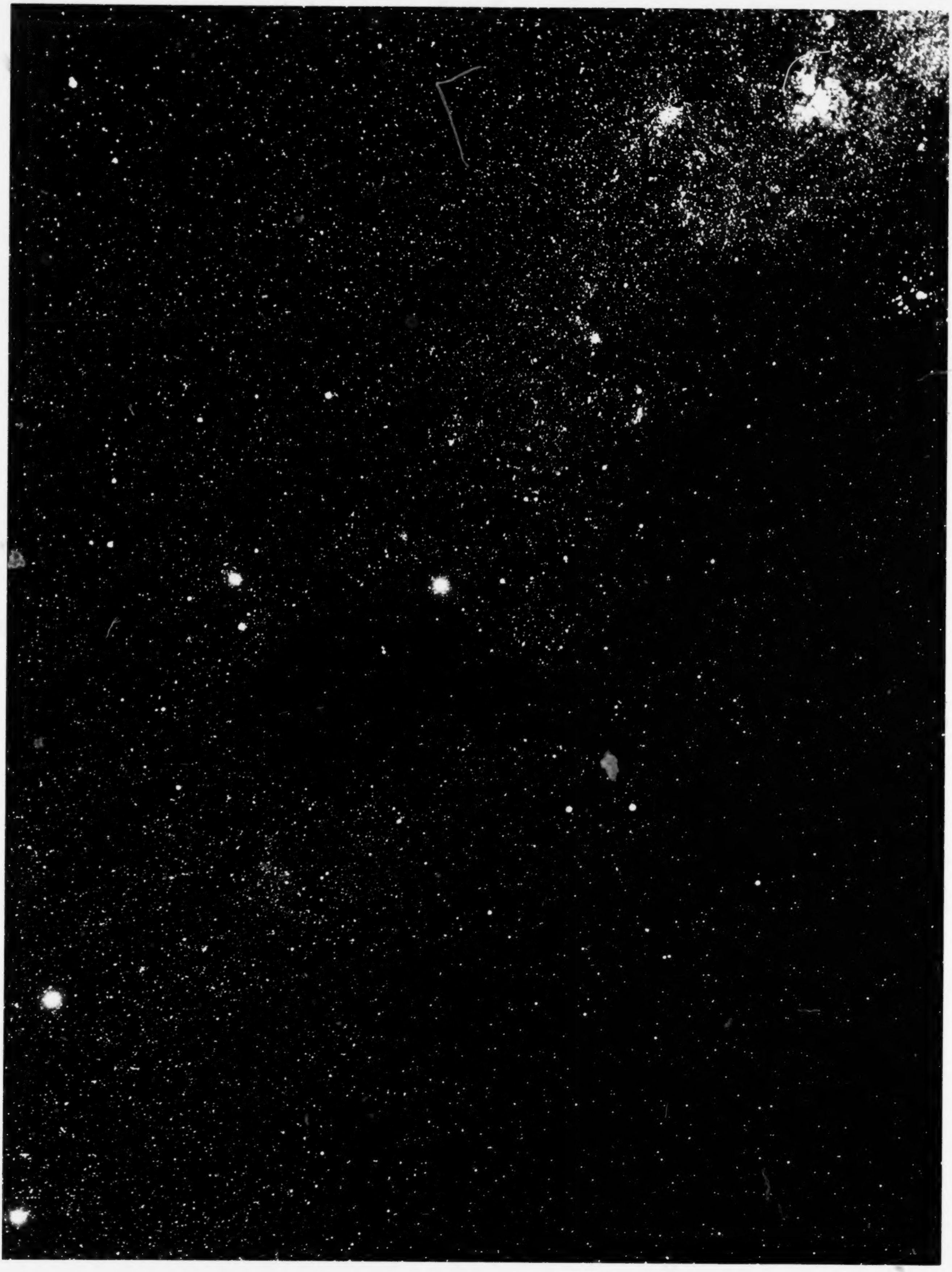

Prologue In Unit 6 we shall dig deeper into the problem of the constitution of matter by studying the atomic nucleus. In Unit 5 we learned that the atom consists of a very small, positively charged nucleus surrounded by electrons. Experiments on the scattering of α particles showed that the nucleus has dimensions of the order of 10^{-14} m. Since the diameter of an atom is of the order of 10^{-10}m, the nucleus takes up only a minute fraction of the volume of an atom. The nucleus, however, contains nearly all of the mass of the atom, as is also shown by the scattering experiments. The existence of the atomic nucleus and its properties raised new questions. Is the nucleus itself made up of still smaller units? If so, what are these units and how are they arranged in the nucleus? What methods can be used to get answers to these questions? What experimental evidence do we have to guide us?

We saw in Unit 5 that the study of the properties and structure of atoms needed new physical methods. The methods that could be used to study the properties of bodies of ordinary size, that is, with dimensions of the order of centimeters or meters, could not yield information about the structure of atoms. It is reasonable to expect that it is still more difficult to get information telling us what, if anything, goes on inside the nucleus, which is such a small part of the atom. New kinds of experimental methods are needed and new kinds of experimental data must be obtained. New theories must be devised to help us correlate and understand the data. In these respects the study of the nucleus is still another step on the long road from the very large to the very small along which we have traveled in this course.

One of the first and most important steps on the road to understanding the atomic nucleus was the discovery of radioactivity in 1896. Our discussion of nuclear physics will, therefore, start with radioactivity. We shall see how the study of radioactivity led to additional discoveries, to the development of methods for getting at the nucleus, and to ideas about the constitution of the nucleus. In fact, the discovery that the atom has a nucleus was a consequence of the study of radioactivity. We shall examine the interaction between experiment and theory and the step-by-step development of ideas about the nucleus. We shall try to see how particular experimental results led to new ideas and how the latter, in turn, led to new experiments. This historical study is especially useful and interesting because nuclear physics is a new branch of physics, which has been developed over a relatively short period of time. The reports and papers in which discoveries have been made known are readily available. The

The energy released by nuclear reactions within stars makes them visible to us over vast distances. The star clouds shown here are over 10,000 light years away. The sun, a typical star, converts over 4 billion kg of hydrogen into radiant energy each second.

research is still going on, and at an ever-increasing rate. Progress in nuclear physics is closely related to modern technology, which both supplies tools for further research and applies some of the results of the research in practical ways. Some of these practical applications have serious economic and political effects, and we read about them almost daily in our newspapers.

When the use and control of nuclear technology is exciting front-page news, it may be hard to realize that the study of the atomic nucleus is connected with a chance discovery made in 1896. But it was that discovery which touched off the whole enterprise that we call nuclear physics, and it is there that we shall start.

Before 1939 the main industrial use of uranium and its compounds was in the manufacture of colored glass, and only small amounts of uranium were needed. The study of the radioactivity of uranium also required only small amounts of uranium ore. As a result, uranium was usually obtained as a not-especially desirable by-product of industrial processes. Since 1939, uranium has become extremely important for reasons we shall discuss in Chapter 24.

Uranium-prospecting can be done using airborne instruments. This method is faster than ground-based prospecting and can be used in many otherwise inaccessible places.

Uranium-ore is mined in both "hard-rock" operations, such as the one in Colorado shown at the left, and in open-pit operations such as the one in New Mexico shown below.

Chapter 21 Radioactivity

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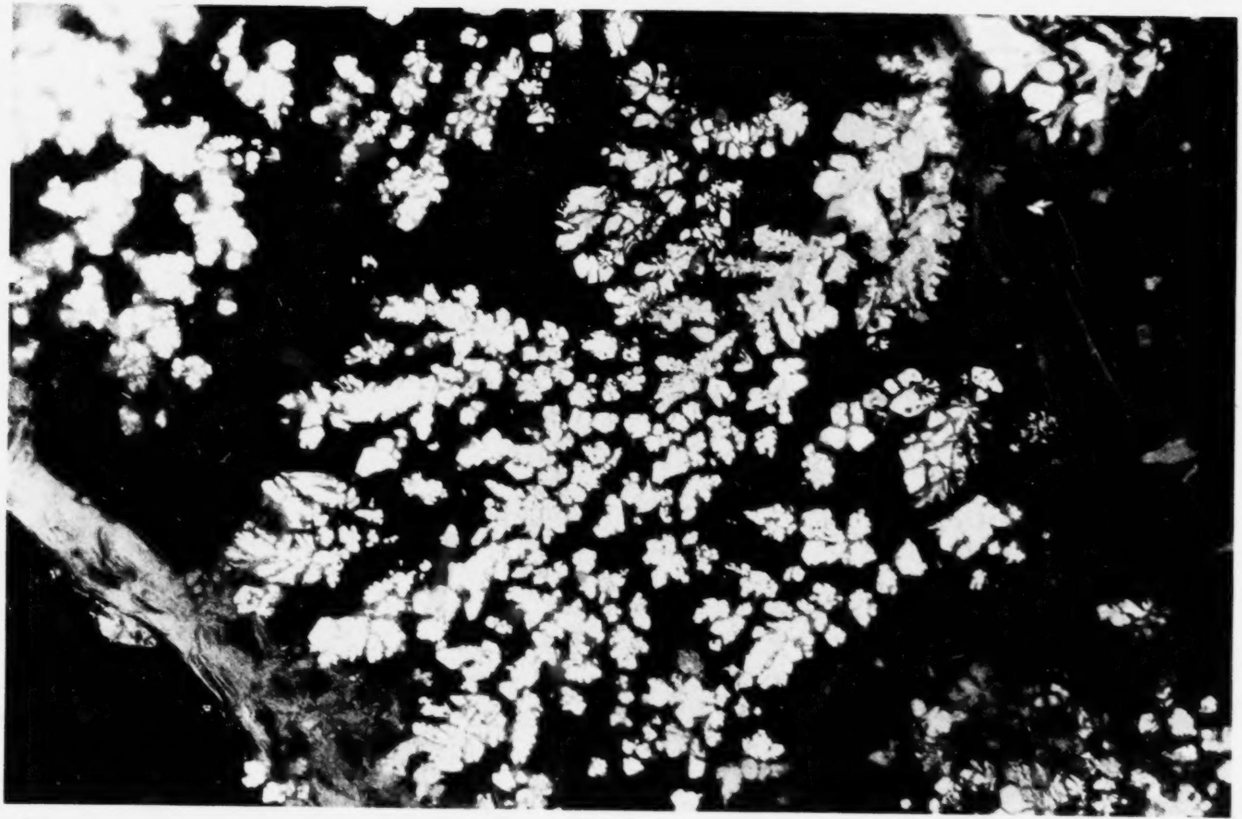
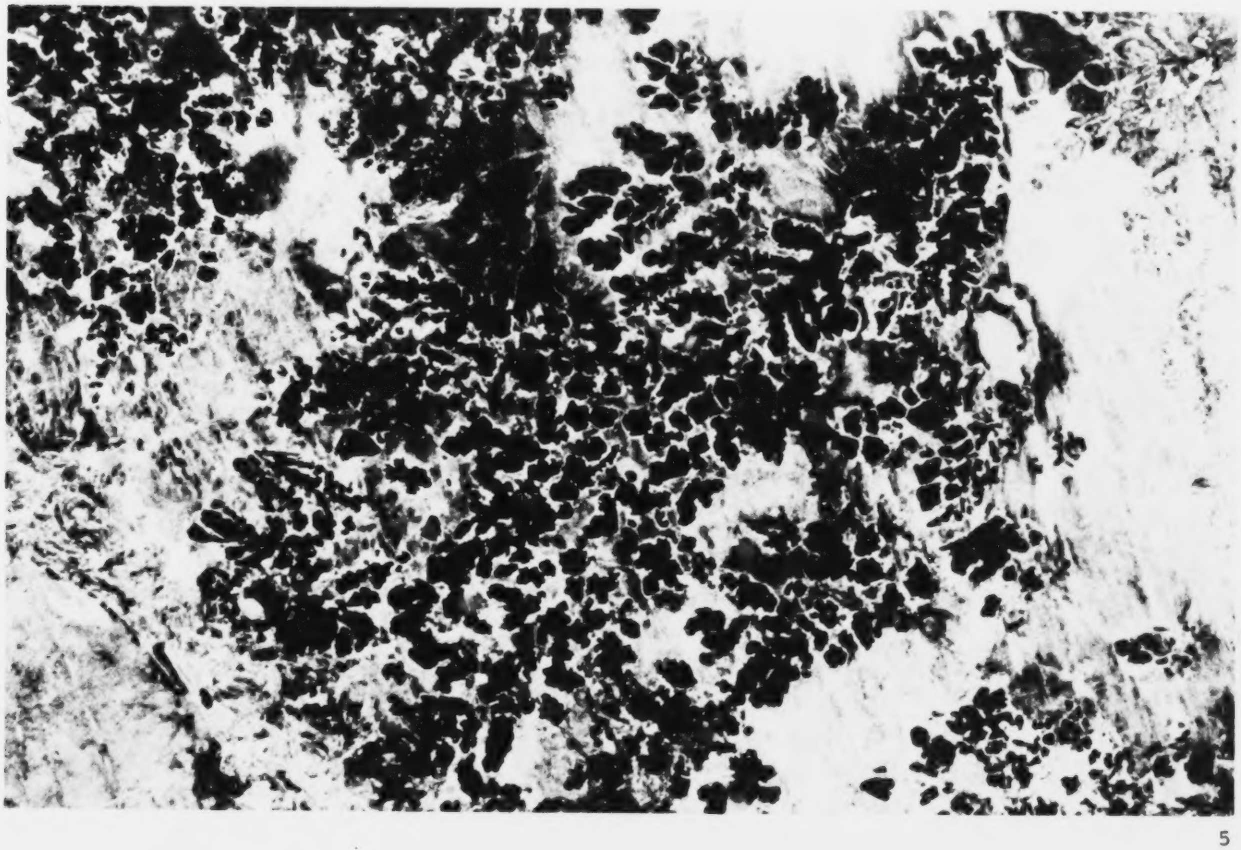


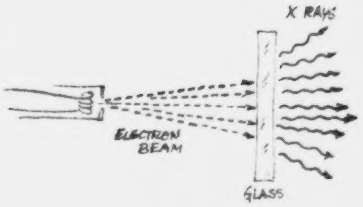
21.1 Becquerel's discovery. The discovery of the phenomenon known as "radioactivity" early in 1896 by the French physicist Henri Becquerel (1852-1908) was another of those "accidents" that illustrate how the trained and prepared mind is able to respond to an unexpected observation. Only two months before, in November 1895, Röntgen had discovered x rays. In doing so, he had set the stage for the discovery of radioactivity. Röntgen had pointed out that x rays came from the spot on the glass tube where the beam of cathode rays (high-speed electrons) was hitting, and that at the same time light was emitted from that spot. When the cathode ray beam was turned off, the spot of light on the face of the glass tube disappeared and the x rays coming from that spot stopped.

The emission of light by the glass tube when it is excited by the electron beam is an example of the phenomenon called fluorescence. A considerable amount of research was done on fluorescence during the latter part of the nineteenth

Below is a photograph of the polished surface of a uranium-bearing rock. On the opposite page is an autoradiograph of the same surface made by placing the rock directly on a piece of film, packaging both in a light-tight container, and allowing the film to be exposed for about fifty hours.

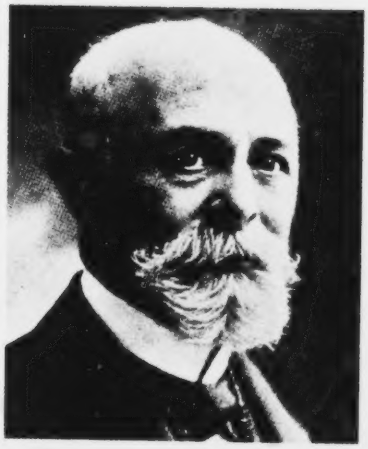


century. A substance is said to be fluorescent if it immediately emits visible light when struck by visible light of shorter wavelength, or by invisible radiations such as ultraviolet light, or by a beam of electrons. Fluorescence stops immediately when the exciting light is turned off. (The term phosphorescence is generally applied to an emission of visible light which continues after the exciting light is turned off.)



X-ray production by bombardment of electrons on glass.

Since the x rays also came from the spot which showed fluorescence it seemed logical to see if there was a closer connection than Röntgen had suspected between x rays and fluorescence or phosphorescence. Becquerel was doubly fortunate in having the necessary materials and training to study this problem. He was the son and grandson of physicists who had made important contributions in the field of phosphorescence. In his Paris laboratory he had devised an instrument for examining materials in complete darkness a small fraction of a second after they had been exposed to a brilliant light. The question occurred to Becquerel: do minerals or other bodies that are made to fluoresce (or phosphoresce) with sufficient intensity also emit x rays in addition to the light rays? He tested a number of substances by exposing them to sunlight and looking to see whether they emitted x rays while phosphorescing. One of them was a salt of the metal uranium, a sample of potassium-uranyl sulfate. In his words:



Henri Becquerel (1852-1908) received the 1903 Nobel Prize in physics (for the discovery of natural radioactivity) along with Pierre and Marie Curie (for the discovery of the radioactive elements radium and polonium).

> I wrapped a...photographic plate...with two sheets of thick black paper, so thick that the plate did not become clouded by exposure to the sun for a whole day. I placed on the paper a [crust] of the phosphorescent substance, and exposed the whole thing to the sun for several hours. When I developed the photographic plate I saw the silhouette of the phosphorescent substance in black on the negative. If I placed between the phosphorescent substance and the paper a coin or a metallic screen pierced with an open-work design, the image of these objects appeared on the negative. The same experiment can be tried with a thin sheet of glass placed between the phosphorescent substance and the paper, which excludes the possibility of a chemical action resulting from vapors which might emanate from the substance when heated by the sun's rays.
>
> We may therefore conclude from these experiments that the phosphorescent substance in question emits radiations which penetrate paper that is opaque to light....

Becquerel was careful to conclude from this experiment only that "penetrating radiations" were emitted from the phosphorescent substance. He did not conclude that the substance emitted x rays while it phosphoresced because he had not yet verified that the radiations were x rays (though the radiations were transmitted through the black paper), or that they were actually related to the phosphorescence (though he strongly suspected that they were). Before he could investigate these possibilities, he made this discovery:

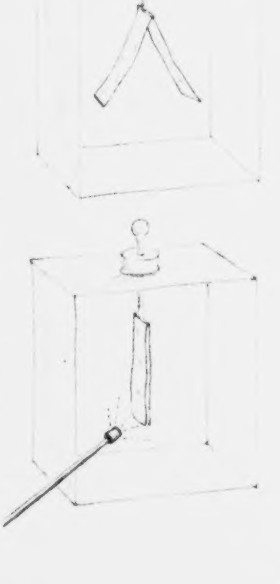
> ...among the preceding experiments some had been made ready on Wednesday the 26th and Thursday the 27th of February [1896]; and as on those days the sun only showed itself intermittently, I kept my arrangements all prepared and put back the holders in the dark in the drawer of the case, and left in place the crusts of uranium salt. Since the sun did not show itself again for several days, I developed the photographic plates on the 1st of March, expecting to find the images very feeble. The silhouettes appeared on the contrary with great intensity. I at once thought that the action might be able to go on in the dark....

Further experiments verified this thought: whether or not the uranium compound was being excited by sunlight to phosphoresce, it continuously emitted something that could penetrate lightproof paper and other substances opaque to light, such as thin plates of aluminum or copper. Becquerel found that all the compounds of uranium—many of which were not phosphorescent at all—as well as metallic uranium itself had the same property. The amount of action on the photographic plate did not depend on the particular compound of uranium used, but only on the amount of uranium present.

Becquerel also found that the radiations from a sample of uranium were persistent and did not change, either in intensity or character, with the passing of time. No change in the activity was observed when the sample of uranium or of one of its compounds was exposed to ultraviolet light, infrared light or x rays. The intensity of the uranium radiation or "Becquerel rays," as they came to be known, was the same at room temperature (20°C), at 200°C and at the temperature at which oxygen and nitrogen (air) liquefy, about -190°C.

Becquerel also showed that the radiations from uranium produced ionization in the surrounding air. They could discharge positively or negatively charged bodies such as electroscopes. Thus, the uranium rays resemble x rays in two important respects: their penetrating power and their ionizing power. Both kinds of rays were invisible to the unaided eye, although they affected photographic plates. But x rays and Becquerel rays differed in at least two important ways: compared to x rays, these newly discovered rays from uranium were less intense, and they could not be turned off. Becquerel showed that even after a period of three years a given piece of uranium and its compounds continued to emit radiations spontaneously.

The air around the charged leaves of the electroscope becomes ionized by radiation from the uranium. The charged particles produced can drift to the leaves and neutralize their charge. The time taken for the leaves to fall is a measure of the rate of ionization of the gas, and hence of the intensity of the α-particle activity.



The years 1896 and 1897 were years of high excitement in physics, to a large extent because of the great interest in x rays and in cathode rays. Since, as quickly became evident, x rays could be used in medicine, they were the subject of much research. But the properties of the Becquerel rays were less spectacular and little work was done on them in the period from the end of May 1896 until the end of 1897. Even Becquerel himself turned his attention to other work. But the fact that the invisible rays from uranium and its compounds could not be turned off began to attract attention.

Two questions were asked: first, what was the source of the energy creating the uranium rays and making it possible for them to penetrate opaque substances? And second, did any other of the seventy or more elements (that were known in 1898) have properties similar to those of uranium? The first question was not answered for some time although it was considered seriously. The second question was answered within a short time by the Curies, who thereby, early in 1898, opened a whole new chapter in physical science.

Q1 **Why was Becquerel experimenting with a uranium compound?**

Q2 **How did uranium compounds have to be treated in order to emit the "Becquerel rays"?**

Q3 **What was the puzzling property of the "Becquerel rays"?**

21.2 Other radioactive elements are discovered.

One of Becquerel's colleagues in Paris was the physicist Pierre Curie, who had recently married a Polish-born physicist, Marie Sklodowska. Marie Curie undertook a systematic study of the Becquerel rays and looked for other elements and minerals that might emit them. Using a sensitive electrometer which her husband had recently invented, she measured the small electric current produced when the rays ionized the air through which they passed. This current was assumed to be (and is) proportional to the intensity of the rays. With this new technique, she could find numerical values for the effect of the rays, and these values were reproducible within a few percent from one experiment to the next. SG 21.1

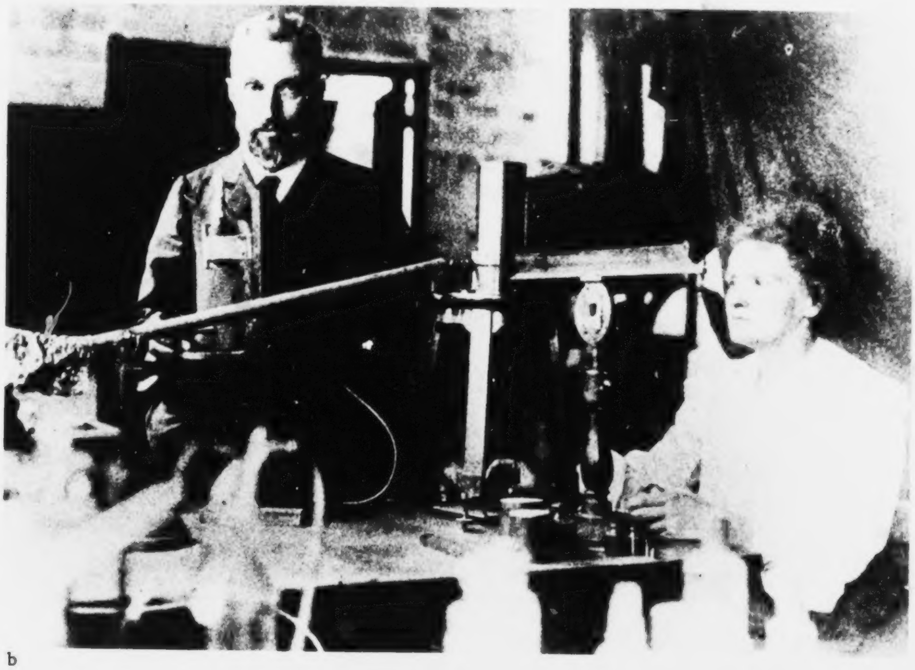
One of her first results was the discovery that the element thorium (Th) and its compounds emitted radiations with properties similar to those of the uranium rays. (The same finding was made independently in Germany by G. C. Schmidt, at about the same time.) The fact that thorium emits rays like those of uranium was of great importance because it showed that uranium was not the only source of the mysterious rays. The discovery spurred the search for still other elements which might emit similar rays. The fact that uranium and thorium were the elements with the greatest known atomic masses indicated that the very heavy elements might have special properties different from those of the lighter elements.

The evident importance of the problems raised by the discovery of the uranium and thorium rays led Pierre Curie to lay aside his researches in other fields of physics and work with his wife on these new problems. They found that the intensity of the emission from any thorium compound was directly proportional to the fraction by weight of the metallic element thorium present. (Becquerel found a similar result for uranium compounds.) Moreover, the amount of radiation was independent of the physical conditions or the chemical combination of the active elements. These results led the Curies to the conclusion that the emission of the rays depended only on the presence of atoms of either of the two elements uranium or thorium. The rate of emission was not affected either by changes of the physical state or by chemical changes of the compounds containing atoms of the elements. To the Curies, these results meant that an explanation of radioactivity lay within the atom itself and not in its chemical combinations. The Curies also deduced that chemical compounds or mixtures containing uranium or thorium are more or less active depending on whether they contain a greater or smaller proportion of these metals. Atoms of other elements that were present were simply inactive or absorbed some of the radiation.

These ideas were especially important because they helped the Curies interpret their later experiments. For example, in their studies of the activity of minerals and ores of uranium and thorium they examined the mineral pitchblende, an ore containing about 80 percent uranium oxide (U_3O_8). They found that the emission from pitchblende, as measured by its effect in ionizing air, was about four or five times as great as that to be expected from the amount of uranium in the ore. The other elements known at the time to be associated with uranium in pitchblende, such as bismuth and barium, had been shown to be inactive. If emission of rays is an atomic phenomenon, the unexpected pitchblende activity could be explained only by the presence in pitchblende of another element more active than uranium itself.

To explore this hypothesis, the Curies applied chemical separation processes to a sample of pitchblende in order to try to isolate this hypothetical active substance. After each separation process, the products were tested, the inactive part discarded and the active part analyzed further.

a



b

a. e. Marie Curie.
b. c. Marie and Pierre.
d. Marie, Irene and Pierre;
all 3 won Nobel prizes!

Pierre Curie (1859-1906) studied at the Sorbonne in Paris. In 1878 he became an assistant teacher in the physical laboratory there, and some years later, professor of physics. He was well known for his research on crystals and magnetism. He married Marie Sklodowska in 1895 (she was 28 years old). After their marriage, Marie undertook her doctoral research on radioactivity. In 1898 Pierre joined his wife in this work. Their collaboration was so successful that in 1903 they were awarded the Nobel Prize in physics, which they shared with Becquerel. Pierre Curie was run over and killed by a horsedrawn vehicle in 1906. Marie Curie was appointed to his professorship at the Sorbonne, the first woman to have this post. In 1911 she was awarded the Nobel Prize in chemistry for the discovery of the two new elements, radium and polonium. She is the only person who has won two Nobel science prizes. The rest of her career was spent in the supervision of the Paris Institute of Radium, a center for research on radioactivity and the use of radium in the treatment of cancer. Marie Curie died in 1934 of leukemia, a form of cancer of the leukocyte-forming cells of the body, probably caused by over-exposure to the radiations from radioactive substances.

c

d

e

21.2

Finally, the Curies obtained a highly active product which presumably consisted mainly of the unknown element. In a note called "On a New Radioactive Substance Contained in Pitchblende" and submitted to the French Academy of Sciences in July of 1898, they reported:

In this note the term "radioactivity" was used for the first time.

> By carrying on these different operations...finally we obtained a substance whose activity is about 400 times greater than that of uranium....
>
> We believe, therefore, that the substance which we removed from pitchblende contains a metal which has not yet been known, similar to bismuth in its chemical properties. If the existence of this new metal is confirmed, we propose to call it polonium, after the name of the native country of one of us.

Six months after the discovery of polonium (given the symbol Po), the Curies separated another substance from pitchblende and found the emission from it so intense as to indicate the presence of still another new element even more radioactive than polonium. This substance had an activity per unit mass 900 times that of uranium and was chemically entirely different from uranium, thorium or polonium. Spectroscopic analysis of this fraction revealed spectral lines characteristic of the inactive element barium, but also a line in the ultraviolet region that did not seem to belong to any known element. The Curies reported their belief that the substance, "although for the most part consisting of barium, contains in addition a new element which produced radioactivity and, furthermore, is very near barium in its chemical properties." For this new element, so extraordinarily radioactive, they proposed the name radium (chemical symbol Ra).

A next step in making the evidence for the newly discovered elements more convincing was to determine their properties, especially the atomic masses. The Curies had made it clear that they had not yet been able to isolate either polonium or radium in pure form, or even to obtain a pure sample of a compound of either element. From the material containing the strongly radioactive substance that they called radium, they had separated a part consisting of barium chloride mixed with a presumably very small quantity of radium chloride. Additional separations gave an increasing proportion of radium chloride. The difficulty of this task is indicated by the Curies' remark that radium "is very near barium in its chemical properties," for it is very difficult to separate elements whose chemical properties are similar. Moreover, to obtain their highly radioactive substances in usable amounts, they had to start with a very large amount of pitchblende.

With an initial 100-kg shipment of pitchblende (from which the uranium salt had been removed to be used in the manufacture of glass) the Curies went to work in an abandoned woodshed at the School of Physics where Pierre Curie taught. Failing to obtain financial support, the Curies made their preparations without technical help in this "laboratory." Marie Curie wrote later:

> I came to treat as many as twenty kilograms of matter at a time, which had the effect of filling the shed with great jars full of precipitates and liquids. It was killing work to carry the receivers, to pour off the liquids and to stir, for hours at a stretch, the boiling material in a smelting basin.

From the mixture of radium chloride and barium chloride only the average atomic mass of the barium and radium could be computed. At first an average value of 146 was obtained, as compared with 137 for the atomic mass of barium. After many additional purifications which increased the proportion of radium chloride, the average atomic mass rose to 174. Continuing the tedious purification process for four years, during which she treated several tons of pitchblende residue, Marie Curie was able to report in July 1902 that 0.1 g of radium chloride had been obtained, so pure that spectroscopic examination showed no evidence of any remaining barium. She determined the atomic mass of radium and obtained the value 225 (the present-day value is 226.03). In 1910, Marie Curie isolated radium metal by means of electrolysis of molten radium chloride. The activity of pure radium is more than a million times that of the same mass of uranium; the present yield of radium from one ton of high-grade uranium ore is about 0.2 g.

Q4 **How is radioactive emission of an element affected by being combined into different compounds?**

Q5 **Why did the Curies suspect the existence of another radioactive material in uranium ore?**

Q6 **What was the main difficulty in producing pure radium?**

21.3 The penetrating power of the radiation: α, β and γ rays.

The extraordinary properties of radium excited interest both inside and outside the scientific world. The number of workers in the field of radioactivity increased rapidly as the importance of the subject and the chance that it seemed to offer of further discoveries came to be recognized. The main question that attracted attention was: what is the nature of the mysterious radiations emitted by radioactive bodies, radiations which can affect photographic plates and ionize air even after passing through solid metal sheets?

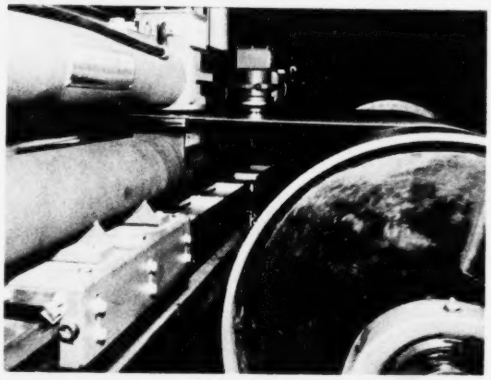
21.3

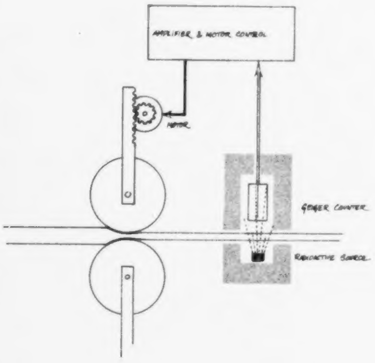
In 1899, Ernest Rutherford, whose theory of the nuclear atom has been discussed in Chapter 19, started to seek answers to this question. He studied the absorption of the radiation from uranium by letting the radiation pass through different thicknesses of aluminum foils. Rutherford thought that the way in which the intensity of the radiation varied with the thickness of the aluminum might indicate whether the rays were of more than one kind. He found that, after the passage of the radiation through 0.002 cm of aluminum, the intensity of the radiation (as measured by the ionization produced in air) was reduced to about one-twentieth of the initial value. The addition of a thickness of 0.001 cm of aluminum had only a very small further effect in cutting down the intensity. The intensity could be reduced further by about one half, by passing the radiation through about fifty times as much foil. Rutherford concluded from these experiments that uranium emits at least two distinct kinds of rays—one that is very readily absorbed, which he called for convenience α rays (alpha rays), and the other more penetrating, which he called β rays (beta rays).

See "Rutherford" in Project Physics Reader 6.

In 1900 the French physicist P. Villard observed that the emission from radium contained rays much more penetrating than even the β rays, this type of emission was given the name γ (gamma) rays. The penetrating power of the three types of rays, as known at the time, is compared in the table below, first published by Rutherford in 1903:

Radiation Type	Approximate thickness of aluminum traversed before the radiation intensity is reduced to one-half its initial value
α rays	0.0005 cm
β rays	0.05 cm
γ rays	8 cm





The absorption of β rays gives rise to many modern practical applications of radioactivity. One example is the thickness gauge illustrated in the photograph and drawing at the right. Sheet metal or plastic is reduced in thickness by rolling. The thickness is measured continuously and accurately by determining the intensity of the β rays that pass through the sheet. The rolling is continued until the desired sheet thickness is obtained.

Of the three kinds of rays, the α rays are the most strongly ionizing and the γ rays the least; the penetration is inversely proportional to the ionization. The penetrating power of the α rays is low because they expend their energy very rapidly in causing intense ionization. Alpha rays can be stopped, that is, completely absorbed, by about 0.006 cm of aluminum, by a sheet of ordinary writing paper or by a few centimeters of air. Beta rays can travel many meters in air, but can be stopped by aluminum less than a centimeter thick. Gamma rays can pass through many centimeters of lead, or through several feet of concrete, before being almost completely absorbed. One consequence of these properties of the rays is that heavy and expensive shielding is sometimes needed in the study or use of radiations, especially γ rays, to protect people from harmful effects of the rays. In some cases these "radiation shields" are as much as 10 feet thick. One example of shielding around a target at the output of an electron accelerator is shown below.

SG 21.2

Q7 **List α, β and γ rays in order of the penetrating ability.**

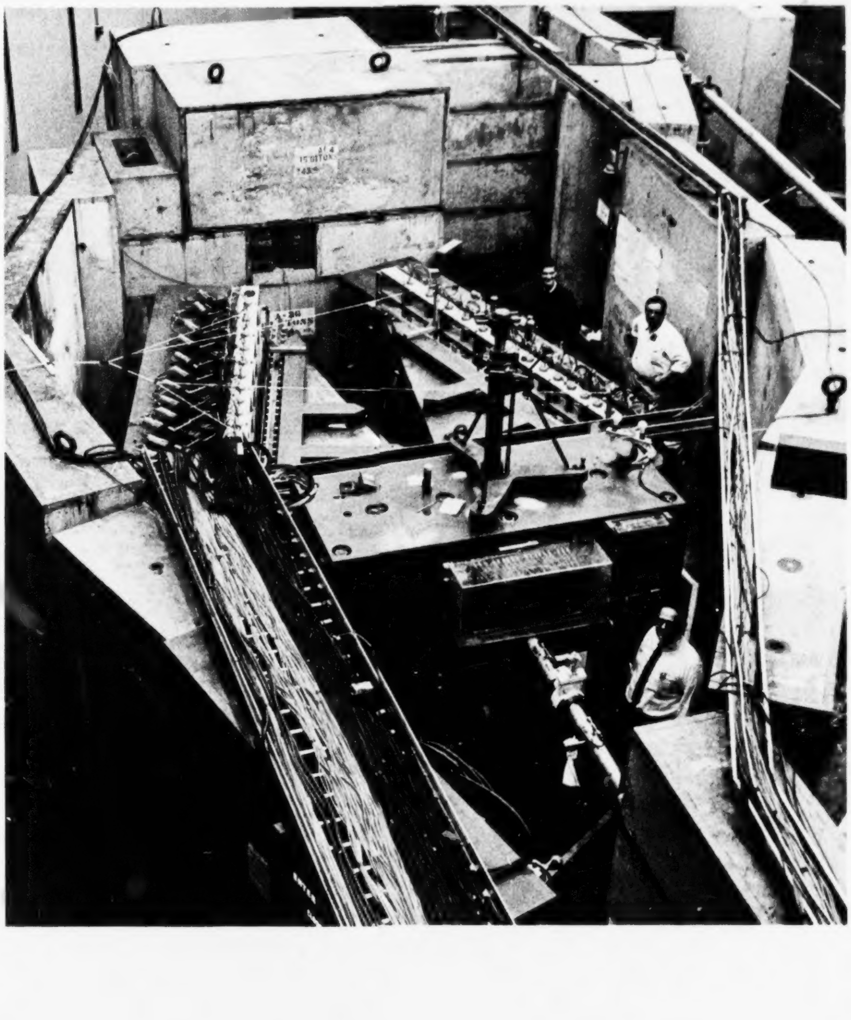
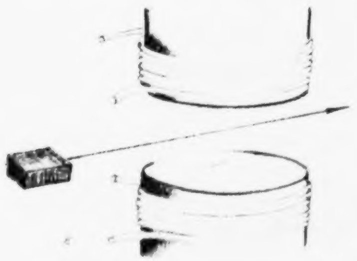
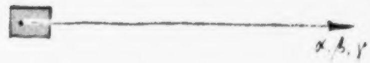


Fig. 21.1 Separation of the α, β and γ rays from a radioactive material by their passage through a magnetic field. (Unless the apparatus were in a vacuum, the path of the α particles would be much shorter than indicated.)

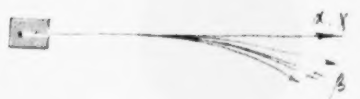


21.4 The charge and mass of α, β and γ rays. Another method used to study the rays was to direct them through a magnetic field to see if they were deflected or deviated from their initial directions by the action of the field. This method, which provides one of the most widely used tools for the study of atomic and nuclear events, is based on the now familiar fact that a force acts on a charged particle moving across a magnetic field. As discussed in Unit 4, this force is always at right angles to the direction of motion of the charged particle. The particle experiences a continual deflection and, in a uniform field, moves along the arc of a circle.

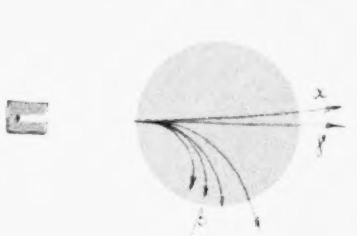
This property had been used in the 1890's by J. J. Thomson in his studies of cathode rays. He showed that these rays consist of very small negatively charged particles, or electrons (Chapter 18). Becquerel, the Curies and others found that the α, β and γ rays behaved differently from one another in a magnetic field. The behavior of the rays is illustrated in the diagrams in the margin.

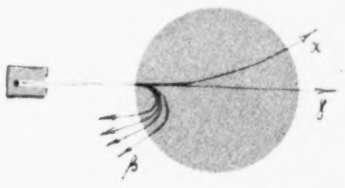


Suppose that some radioactive material, such as uranium, is placed at the end of a narrow hole in a lead block; a narrow beam consisting of α, β and γ rays escapes from the opening. If a strong, uniform magnetic field is applied perpendicular to the plane of the page away from the reader, the three types of rays are separated from each other. The γ rays continue in a straight line without any deviation. The β rays are deflected strongly downwards, moving in circular arcs of differing radii. The α rays are bent slightly upwards in a circular arc of large radius, but are rapidly absorbed in the air after moving only a few centimeters from the lead block.



The direction of the deflection of the β rays was the same as that observed earlier in Thomson's studies of the properties of cathode rays. It was concluded, therefore, that the β rays, like cathode rays, consist of negatively charged particles. Since the direction of the deflection of the α rays was opposite to that of the β rays, it was concluded that the α rays consist of positively charged particles. Since the γ rays were not deflected, it was concluded that they were neutral, that is, had no electric charge; no conclusion could be drawn from this type of experiment as to whether the γ rays are, or are not, particles. The magnitude of the deflections suggests that the α particles have a much larger momentum than the β particles. The conclusions concerning the signs of the electric charges carried by the rays were tested by directing the deflected beam into an electroscope and determining the





charge that builds up on the leaves. This was done by the Curies in 1900 to confirm the negative charge of the β particles.

The q/m for the beta particles could be found from their deflection in magnetic and electric fields. Becquerel, investigating β particles in 1900, used a procedure which was essentially the same as that used by J. J. Thomson in 1897 to obtain a reliable value for the ratio of charge q_e to mass m_e for the particles in cathode rays (thereby establishing quantitatively the existence of the electron). By sending β rays through crossed electric and magnetic field, he was able to calculate the speed of the β particles. He obtained a value of q/m for β particles which was in close enough agreement with that found by J. J. Thomson for the electron to permit the deduction that the β particles are electrons.

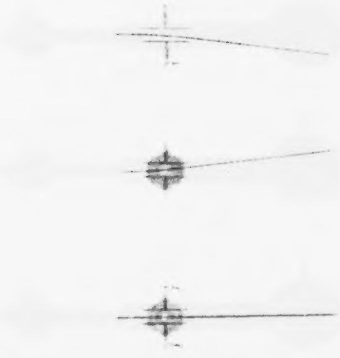


Fig. 21.2 If an electric field and a magnetic field are at right angles, each will deflect charged particles. There will be only one speed for which there will be no deflection.

The nature of the α radiation was more difficult to establish. The value of q/m for α particles (4.8×10^7 coul/kg) was about 4000 times smaller than q/m for β particles. It was therefore necessary to use a very strong magnetic field to produce measurable deflections. Other evidence available at the time indicated that q for an α particle was not likely to be smaller than for a β particle. It was therefore concluded that m would have to be much larger for the α particle than for the β particle. SG 21.3 SG 21.4

In fact, the value of q/m given above for α particles is just one half that of q/m for a hydrogen ion. The value would be explained in a reasonable way if the α particle were like a hydrogen molecule minus one electron (H_2^+), or else if it were a helium atom (whose mass was known to be about four times that of a hydrogen atom) without its two electrons (He^{++}). Other possibilities might have been entertained—for example, bare nuclei of carbon, nitrogen or oxygen would have about the same q/m ratio. But there were other reasons for thinking that α particles were related to helium.

Q8 **What was the evidence that β particles are electrons?**

Q9 **What observation led to the suggestion that α particles are much more massive than β particles?**

21.5 The identity of α rays: Rutherford's "mousetrap." It was known that the gas helium was always found imprisoned in radioactive minerals. In addition, Sir William Ramsey and Frederick Soddy had discovered, in 1903, that helium was liberated by a radioactive compound, radium bromide. Rutherford made the hypothesis that the α particle is a doubly-ionized helium atom—a He atom minus two electrons—or, as we would now say, the nucleus of a helium atom. In a series of experiments from 1906 to 1909 he succeeded in proving the correctness of his hypothesis in several different ways. The last and most convincing of these experiments was made in 1909, with T. D. Royds, by constructing what Sir James Jeans later called "a sort of mousetrap for α particles."

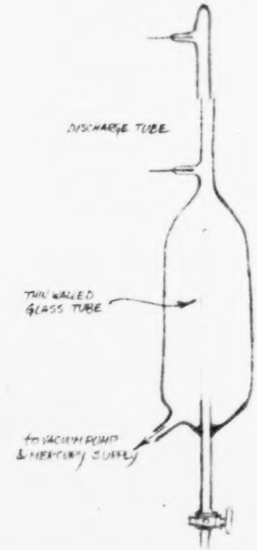
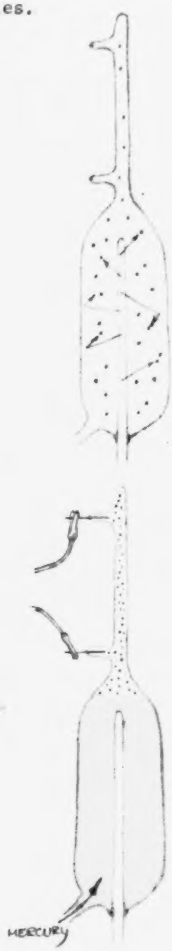


Fig. 21.3 Rutherford's "mousetrap" for identifying α particles.



The experiment was based on the use of the radioactive element radon (Rn), which has properties that made it especially suitable for the experiment. Radon was discovered by Pierre Curie and A. Debierne in 1901. They placed some radium in a glass vessel and pumped air out of the vessel until the air pressure was very low. They then found that the pressure in the vessel increased because a gaseous substance was given off from the radium. A small amount of the gas collected in this way was found to be a strong α particle emitter. The gas was shown to be a new element and was called "radium emanation" and later "radon." Ramsey and Soddy showed that when this radon is stored in a closed vessel, helium always appears in the vessel. Thus helium is given off not only by radium bromide but also by radon.

Rutherford and Royds put a small amount of radon in a fine glass tube with a wall only one hundredth of a millimeter thick. This wall was thin enough so that α particles could pass through it. The tube was sealed into a thick-walled glass tube which had a discharge tube at the top. Fig. 21.3 shows diagrams of the apparatus. The air was pumped out of the outer tube and the apparatus was allowed to stand for about a week. During this time, while α particles from the radon passed through the thin walls of the inner tube, a gas gradually collected in the previously evacuated space. Mercury was then used to compress the gas and confine it in the discharge tube. When a potential difference was applied to the electrodes of the discharge tube, an electric discharge was produced in the gas. The resulting light was examined with a spectroscope and the spectral lines characteristic of helium were seen. In a separate control experiment, helium gas itself was put in the inner, thin-walled tube instead of radon, and did not leak through the wall of the inner tube.

Now it was clear how to interpret the results of these experiments: Rutherford could safely conclude that the helium gas that collected in the outer tube was formed from α particles that had passed into the outer tube. Even at low gas pressures electrons were present so that the α particles could form neutral helium atoms by capturing electrons.

Rutherford's conclusion implied that an atom of an element (radon) spontaneously emits a fragment (an α particle) which consists of the nucleus of *another* element (helium). The result implied that a *transmutation*, the production of one element from another, occurs when radon emits an α particle.

See "The Nature of the Alpha Particle" in Project Physics Reader 6.

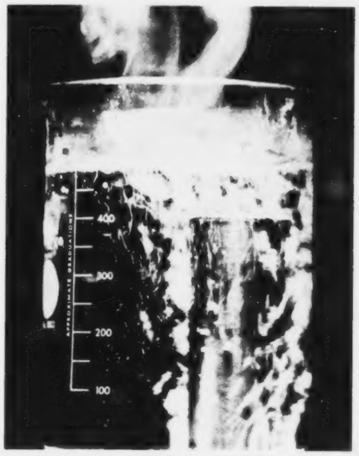
Q10 How did Rutherford know that the gas which appeared in the tube was helium?

21.6 *Radioactive transformations*.

The emission of α and β particles presented difficult and important questions with respect to existing ideas of matter and its structure. The rapid development of chemistry in the nineteenth century had made the atomic-molecular theory of matter highly convincing. According to this theory, a pure element consists of identical atoms, and these atoms are indestructible and unchangeable. But, if a radioactive atom emits an α particle (shown to be an ionized helium atom), can the radioactive atom remain unchanged? The answer seems clearly to be "no"; a transmutation must take place in which the radioactive atom is changed to an atom of a different chemical element.

If an atom emits an α particle, a substantial part of its mass will be carried away by the α particle. What about the atoms which emit β particles? The β particle is not as massive as the α particle but its mass is not zero, and a radioactive atom must undergo some change when it emits a β particle. It was difficult to escape the conclusion that all radioactive atoms are, in fact, subject to division (into two parts of markedly unequal mass), a conclusion contrary to the basic concept that the atom is indivisible.

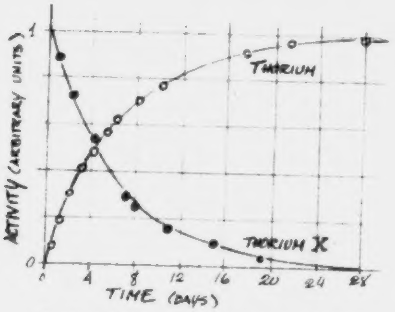
Another fundamental question arose in connection with the energy carried by the rays emitted by radioactive substances. As early as 1903 Rutherford and Soddy, and Pierre Curie and a young co-worker, A. Laborde, noted that radium emitted a large amount of energy—so large that a sample of radium kept itself at a higher temperature than the surrounding air merely by absorbing some of the energy of the α particles emitted by atoms in the sample. Curie and Laborde found that one gram of radium releases about 100 calories of heat per hour (or 0.1 kilocalorie). Radium has the remarkable property that it can continue to release energy year after year, for hundreds and even thousands of years.



The water is being boiled by the heat produced by a small capsule of cobalt 60. This capsule, the first ever made to produce heat from radioactive cobalt, generated heat at the rate of 360 watts when this photo was taken.

The continuing release of such a quantity of heat could not be explained by treating radioactivity as if it were an

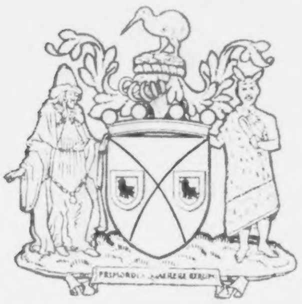
In 1900, the English physicist Sir William Crookes found that most of the observed activity of pure compounds of uranium was not due to that element, but to something else which could be separated chemically from the uranium. This active "something else" was called uranium X to distinguish it from uranium. Becquerel then separated the two substances and found that the activity of the uranium X decreased while that of the uranium increased. Rutherford and Soddy, of whom we shall hear more in Chapter 22, obtained similar results with compounds of thorium. Their results, published in 1903, are shown below.



Rutherford and Soddy received the Nobel prize in chemistry for their work on the radioactive transformation of one element into another.

In 1931 Rutherford was elevated to the British peerage becoming "Baron Rutherford of Nelson." It is said some similarity between parts of his coat of arms and the diagram above has been intentionally preserved.

RUTHERFORD OF NELSON.



21.6

ordinary chemical reaction. It was also clear that radioactivity did not involve chemical changes in the usual sense: energy was emitted by samples of pure elements; energy emission by compounds did not depend on the type of molecule in which the radioactive element was present. The origin of the production of heat had to be sought in some deeper changes within the atoms themselves.

Rutherford and Soddy proposed a bold theory of radioactive transformation to explain the nature of these changes. They proposed that when a radioactive atom emits an α or a β particle it really breaks into two parts—the α or β particle emitted, and a heavy left-over part, or residue, which is physically and chemically different from the "parent" atom. There was a good deal of evidence for the last part of the assumption. For example, there was the formation of radon from radium, discussed earlier. When the atomic mass of radon was determined, it turned out to be smaller than that of radium by just 4 atomic mass units, the mass of an α particle.

According to the proposal of Rutherford and Soddy, the formation of radon may be represented by means of a diagram:

$$\begin{tikzcd}
 & \alpha & \\
\mathrm{Ra} \arrow[ur] \arrow[rr] & & \mathrm{Rn} .
\end{tikzcd}$$

In the diagram, Ra stands for an atom of radium and Rn for an atom of radon. An equation analogous to a chemical equation may be used equally well:

$$\mathrm{Ra} \longrightarrow \mathrm{Rn} + \mathrm{He} \quad .$$

Here He stands for the helium atom formed when the α particle picks up two electrons and becomes neutral. The process may be described as the "disintegration" or "decay" or "transmutation" of radium into radon, with the emission of an α particle.

In addition to the example just cited, many decay processes had been found and studied, by the Curies, by Rutherford and his co-workers, and by others, and these processes fitted easily into the kind of scheme proposed by Rutherford and Soddy. Radon also is radioactive, emitting an α particle and thereby decaying into an atom of an element which was called "radium A" at the time. Radium A was shown to be polonium (Po).

$$\mathrm{Rn} \longrightarrow \mathrm{Po} + \mathrm{He} \ .$$

Polonium is a solid, and also is radioactive. In fact, the original radium atoms undergo a series or chain of transformations into new, radioactive, "daughter" elements, ending with a "daughter" element which is stable, or non-radioactive. SG 21.5

Q11 Why couldn't radioactive decay be an ordinary chemical reaction?

Q12 What was it about the products of decay that indicated nuclei were being transmuted?

21.7 Radioactive decay series. The stable end-product of the decay of radium and its daughters was identified by its chemical behavior as lead. The chain beginning with radium has 10 members, some of which emit β particles rather than α particles. Gamma rays do not appear alone, but always together with an α particle or a β particle. Rutherford and Soddy also suggested that, since radium is always found in uranium ores, it may be a member of a series starting with uranium as the ancestor of all the members. Research showed that this is indeed the case. Each uranium atom may in time give rise to successive daughter atoms, radium being the sixth generation and stable lead the fifteenth.

Table 21.1 shows the members of the uranium-radium series. The significance of some of the symbols will be discussed in later sections. The number following the name of an element, as in uranium 238, indicates the atomic mass. Notice that there are heavier and lighter varieties of the element, for example, uranium 238 and 235, polonium 218, 214 and 210. Much more will be said about these varieties in the next chapter.

Two other naturally occurring radioactive series have been found; one starts with thorium 232 and the other with uranium 235 (see SG 22.7 and 22.8).

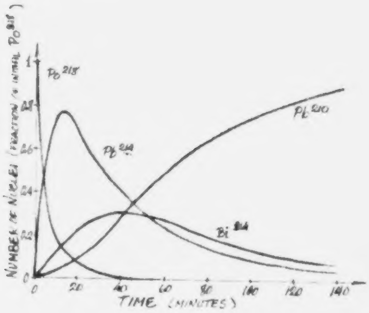
There is also a fourth series starting with artificially produced plutonium (see SG 22.9).

Table 21.1

Uranium-radium series

Old name	Present name and symbol		Mode of decay	Half-life
Uranium I	Uranium 238	${}_{92}U^{238}$	α	4.51×10^{9} years
Uranium X_1	Thorium 234	${}_{90}Th^{234}$	β, γ	24.1 days
Uranium X_2	Protactinium 234	${}_{91}Pa^{234}$	β, γ	1.18 minutes
Uranium II	Uranium 234	${}_{92}U^{234}$	α	2.48×10^{5} years
Ionium	Thorium 230	${}_{90}Th^{230}$	α, γ	8.0×10^{4} years
Radium	Radium 226	${}_{88}Ra^{226}$	α, γ	1620 years
Radium emanation	Radon 222	${}_{86}Rn^{222}$	α	3.82 days
Radium A	Polonium 218	${}_{84}Po^{218}$	α	3.05 minutes
Radium B	Lead 214	${}_{82}Pb^{214}$	β, γ	26.8 minutes
Radium C	Bismuth 214	${}_{83}Bi^{214}$	β, γ	19.7 minutes
Radium C′	Polonium 214	${}_{84}Po^{214}$	α	1.64×10^{-4} seconds
Radium D	Lead 210	${}_{82}Pb^{210}$	β, γ	21.4 years
Radium E	Bismuth 210	${}_{83}Bi^{210}$	β	5.0 days
Radium F	Polonium 210	${}_{84}Po^{210}$	α, γ	138.4 days
Radium G	Lead 206	${}_{82}Pb^{206}$	stable	

Each member of the series differs physically and chemically from its immediate parent or daughters; it should, therefore, be possible to separate the different members of the chain. But the separation problem was made difficult by the fact that the different radioactive species decay at different rates, some very slowly, some rapidly, others at intermediate rates. These rates and their meaning will be discussed in the next section.



An interesting example is supplied by the portion of the uranium series starting with the substance called polonium 218. A pure sample may be collected by exposing to radon a piece of ordinary material such as a thin foil of aluminum. Some of the radon atoms decay into polonium 218 atoms which are deposited on the surface of the foil. The graph at the left shows what becomes of the polonium 218. Polonium 218 decays into lead 214, which decays into bismuth 214, which decays into polonium 214, then lead 210, etc. If the original sample contains 1,000,000 atoms of polonium 218 when it is formed, after twenty minutes it will contain about 10,000 polonium 218 atoms, about 660,000 lead 214 atoms, about 240,000 bismuth 214 atoms and about 90,000 lead 210 atoms. The number of polonium 214 atoms is negligibly small because most of the polonium 214 changes into lead 210 in a small fraction of a second. The numbers of atoms of these radioactive substances change with time, quite rapidly in this particular case. A sample of pure, freshly separated radium (Ra 226) would also change in composition in a complicated way, but much more slowly. Eventually it would consist of a mixture of radium 226, radon 222, polonium 218, lead 214 and all the rest of the members of the chain down to, and including, stable "radium G" (lead). A sample of pure uranium may contain, after a time, 14 other elements of which 13—all but the last, stable portion—contribute to the radioactive emission, each in its own way. A complicated mixture of elements results and many α particles, β particles and γ rays are emitted, apparently continuously and simultaneously.

In 1898 the Curies obtained a total of about 200 grams of radium. Seventy years later (1968) 194 grams of this remain as radium. The six grams of radium that have been lost correspond to 16 x 10^{21} radium atoms that have decayed into radon and subsequently into other elements during these 70 years.

SG 21.6

It is therefore evident that the separation of the different members of a radioactive chain is extremely difficult—especially if some members of the chain decay rapidly. The determination of the chemical nature and the radioactive properties of each member requires the greatest experimental ingenuity. One successful method depends on the skillful purification of a particular radioactive substance, as the Curies had done with radium and polonium. For example, suppose that a sample has been obtained from which all the radioactive substances except radium have been removed. The sample immediately starts to give off radon gas. The latter can be drawn off and its properties examined before it becomes seriously contaminated by the disintegration of many of its atoms into polonium 218. If this is done, it turns out that radon decays (through several transformations) into lead much more quickly than radium decays into radon.

Q13 Give at least 3 reasons for the difficulty of separating decay products.

21.8 Decay rate and half-life. In the last section we saw that of 1,000,000 polonium 218 atoms present in a freshly prepared sample of that radioactive substance, only about 10,000 would remain after twenty minutes, the rest having decayed into atoms of lead 214. At the end of only three minutes following preparation of the sample, fifty percent of the atoms originally present in the sample would remain, the other fifty percent having already decayed. But it would take 1620 years for half of the radium atoms in a freshly prepared sample of radium to be transformed into radon atoms. The two substances radium 226 and polonium 218 illustrate the experimental fact that radioactive elements show great differences in their rates of decay. In addition, different atoms of a given element decay at different times; some decay as soon as they are produced, while others may never decay. But, in a sample consisting of an extremely large number of any given kind of radioactive atom, it has been found experimentally that the fraction of the number of atoms of that kind that decay per second is characteristic, fixed and unchangeable; it is independent of all physical and chemical conditions, such as temperature, pressure and form of chemical combination. These remarkable properties of radioactivity deserve special attention, and the meaning of the underlined statement above will be discussed in detail because it is basic to our understanding of radioactivity.

The ratio of the activity to the total number of original atoms is the fraction of the original number of atoms that has decayed per unit time. This ratio is analogous to the death rate—in the case of the United States, about 5000 persons per day in a population of 200 million, or one person per 60,000 per day.

Since the fraction of the atoms that decay per unit time is constant, the number of atoms that decay per unit time must decrease in proportion to the number of atoms remaining.

21.8

If the number of surviving atoms is plotted as a function of time, a curve such as that shown at the left is obtained.

The curve that shows the number of atoms that have not decayed as a function of time approaches the time axis asymptotically; that is, the number of survivors becomes small but never becomes zero. This is another way of saying that we cannot assign any definite time at which the value of N falls to zero. The smaller the number of unchanged atoms, the smaller is the number that decay per unit time.

It is possible to specify the time required for any particular fraction of a sample to decay—say 1/2 or 1/3 or 37%, for instance. For convenience in making comparisons, the fraction 1/2 has been chosen. The time T required for the decay of one-half the original atoms of a pure sample, Rutherford called the half-life. Each kind of radioactive atom has a unique half-life, and thus the half-life of a substance can be used to identify a radioactive substance. As Table 21.1 shows, these half-lives vary widely.

For the parent of the uranium series, the half-life is 4.5 billion years. This means that, after 4.5×10^9 years, half of the uranium 238 atoms will have decayed. For polonium 214 the half-life is of the order of 1/10,000 of a second. If pure samples of each, containing the same number of atoms, were available, the initial activity of polonium 214 would be very strong and that of uranium 238 very feeble. If left for even a minute, though, the polonium would have decayed so rapidly and the number of the surviving atoms would be so small, that the activity due to polonium would be less than the activity of the uranium. We can speculate that some radioactive elements, present in great quantities long ago, decayed so rapidly that no measurable traces are now left. Many radioactive elements decay so slowly that during any ordinary experimentation time their decay rates seem to be constant.

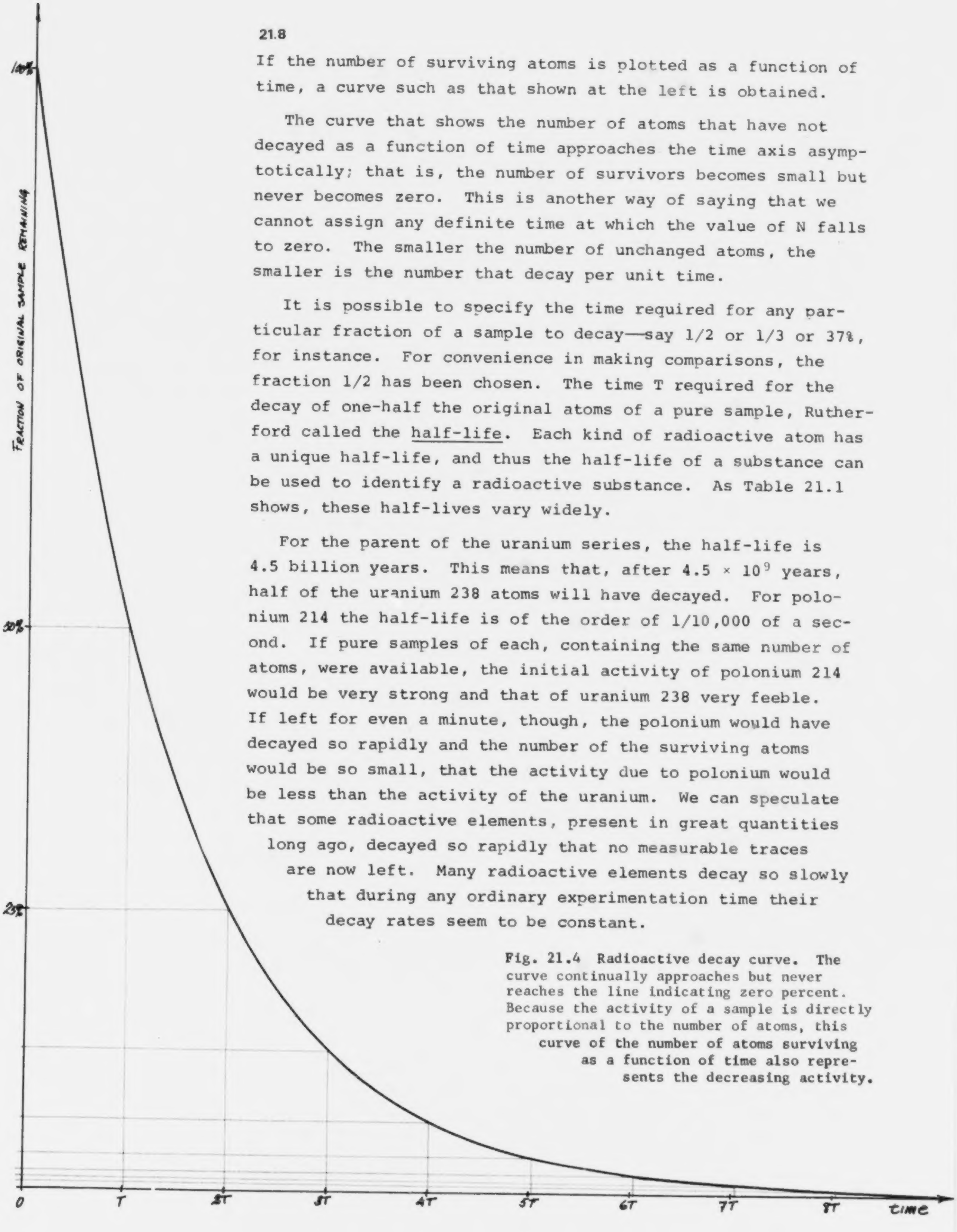


Fig. 21.4 Radioactive decay curve. The curve continually approaches but never reaches the line indicating zero percent. Because the activity of a sample is directly proportional to the number of atoms, this curve of the number of atoms surviving as a function of time also represents the decreasing activity.

The principal advantage of the concept of half-life lies in the experimental result implied in Fig. 21.4 that, no matter how old a sample with given half-life T is at a given moment, in an additional time interval T, half of the existing atoms will still survive. Thus, the half-life is not to be thought of as an abbreviation for "half a life." If one-half the original atoms remain unchanged after a time T, one-fourth (1/2 × 1/2) will remain after two consecutive half-life intervals 2T, one-eighth after 3T, and so on. Note how different the situation is for a population of, say, human beings instead of radioactive atoms. If we select a group of N_0 babies, half the number may survive to their 70th birthday; of these $N_0/2$ oldsters, none is likely to celebrate a 140th birthday. But of N_0 radioactive atoms with a half-life of 70 years, $N_0/4$ will have remained intact after 140 years, $N_0/8$ after 280 years, etc. The statistical probability of survival for atoms is unchanged by the age they have already reached; in humans, the probability of survival depends strongly on age.

SG 21.7
SG 21.8
SG 21.9
SG 21.10

We are not considering here the behavior of individual atoms, but the behavior of a very large number. If a hundred thousand persons were to flip coins simultaneously just once, we could predict with good accuracy that about one-half of them would get heads. But we could not accurately predict that one particular person in this crowd would obtain heads on a single flip. If the number of coins tossed is small, the observed count is likely to differ considerably from the prediction of 50% heads. From experiments in radioactivity we can predict that a certain fraction of a relatively large number of atoms in a sample will survive in any given time interval—say, 1/2 will survive to reach the age T—but not whether a particular atom will be among the survivors. And as the sample of survivors decreases in size owing to disintegrations, our predictions about the fraction of survivors become less accurate; finally, when only a few atoms remain unchanged, the predictions are no longer meaningful. In short, the disintegration law is a statistical law, and is thus applicable only to large populations of the radioactive atoms, not to the decay of individual atoms. It makes no assumptions as to why the atoms disintegrate. The use of this statistical law is justified because even a minute sample of a radioactive element contains very many atoms. For example, one-millionth of a gram of uranium contains 2.53×10^{15} atoms.

In the discussion of the kinetic theory of matter we saw

The Mathematics of Decay

The beautifully simple mathematical aspect of decay is that the fraction of atoms decaying per second doesn't change with time. If initially there are N_o atoms, and a certain fraction λ* of them decay in one second, the number of atoms decaying in one second is λN_o. Then at any later time t, when there are only N_t atoms remaining, the fraction that decay in one second will still be λ, but the number of atoms decaying in one second is now λN_t. The constant fraction of atoms decaying per unit time is called the decay rate. The value of this rate λ can be found for each radioactive species. For example, λ for radium is 1.36×10^{-11} per second, which means that of any sample of radium atoms, on the average 0.0000000000136 of the total number in the sample will decay in one second.

$$N_t = N_o e^{-\lambda t}$$

$$\frac{N_t}{N_o} = e^{-\lambda t}$$

$$\log\left(\frac{N_t}{N_o}\right) = -\lambda t \log e$$

$$\text{at time T,} \quad \frac{N_t}{N_o} = \frac{1}{2}$$

$$\log\left(\frac{1}{2}\right) = -\lambda T \log e$$

$$-0.301 = -\lambda T\,(0.4343)$$

$$\lambda T = 0.693$$

This constant fractional decay rate can be represented by the following mathematic expression: $N_t = N_o e^{-\lambda t}$, or $N_t/N_o = e^{-\lambda t}$, where e is a mathematical constant = 2.718. Since the decay rate λ appears as an exponent, this expression is an "exponential" equation and is said to represent the "exponential decay" illustrated by the graph which frames p. 24.

The half-life T is related to the decay rate λ; the relationship can be derived as follows. We start by writing the exponential decay equation in logarithmic form. This is done by taking the logarithm of both sides of the equation. Log $(N_t/N_O) = -\lambda t \log e$. After the half-life T, the ratio $N_t/N_O = \frac{1}{2}$. So we can substitute $\frac{1}{2}$ for N_t/N_O if we substitute T for t in the equation: $\log(\frac{1}{2}) = -\lambda T \log e$. This equation can be simplified by realizing that $\log(\frac{1}{2})$ is -0.30i and $\log e = 0.4343$: $-0.301 = -\lambda T\,(0.4343)$. Thus, $\lambda T = 0.693$. We therefore find that the product of the decay rate and the half-life is always equal to 0.693.

For example, radium has a decay rate $\lambda = 1.36 \times 10^{-11}$ per second, so the half-life T of radium is $0.693/1.36 \times 10^{-11}$ per second, which is equal to 5.10×10^{10} sec or about 1690 years.

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*There is no relation between the use of the symbol λ for decay rate and the use of λ for wavelength.

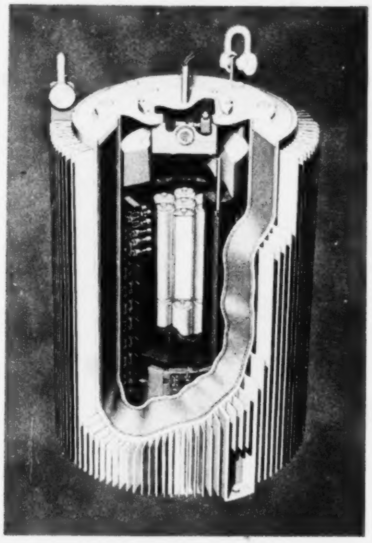
that it is a hopeless task to try to describe the motions of each individual molecule, but we could calculate the average pressure of a gas containing a very large number of molecules. Similarly, in dealing with radioactivity we find that our inability to specify when each of the tremendous number of atoms in a normal sample will disintegrate makes a statistical treatment necessary.

SG 21.11
SG 21.12

Q14 How much of a substance will be left after four of its half-lives?

Q15 If, after many many half-lives, only two atoms of a radioactive substance remain, what will happen during the next half-life?

An early SNAP (Systems for Nuclear Auxiliary Power) generator installed in a Navy Transit 4-A navigational satellite. The spontaneous fission of plutonium 238 supplies a continuous flow of heat which is converted to electricity by thermocouples.



This cutaway view of a SNAP-7 generator shows how thermocouples are arranged to convert heat from the radioactive strontium 90 cores directly to electrical energy. The outer wall is a thick metal shield designed to absorb radiation from the strontium 90, and the fins dissipate excess heat to keep the assembly at the design temperature. Most SNAP devices are built to produce a steady flow of electrical energy for a period of several years, so they are particularly adapted for use in satellites, untended lighthouses, ocean buoys and similar applications.

21.1 Which of the Curies' discoveries would have been unlikely if they had used Becquerel's photographic technique for detecting radioactivity?

21.2 A spectroscopic examination of the γ rays from bismuth 214 shows that rays of several discrete but different energies are present. The rays are said to show a "line spectrum." The measured wavelength corresponding to one of the lines is 0.016Å.

a) Show that the energy of each of the γ-ray photons responsible for that line is 1.2×10^{-13} J. (Hint—see chapter 20.)
b) What is the equivalent energy in electron volts?

21.3 Suppose that in Fig. 21.1 the magnetic field strength is 1.0×10^{-3} N/amp·m.

a) What would be the radius of curvature of the path of electrons entering the magnetic field with a speed of 1.0×10^{7} m/sec? (The charge and mass of the electron are 1.6×10^{-19} coul and 9.0×10^{-31} kg respectively.)
b) If α particles entered the magnetic field with the same speed as the electrons in part (a), what would be the radius of curvature of their orbit? (The mass of an α particle is 6.7×10^{-27} kg.)
c) Compare your answers to parts (a) and (b).

21.4 If the electrons described in part (a) of the previous problem pass through crossed electric and magnetic fields as shown in the lower sketch of Fig. 21.2,

a) what must be the strength of the electric field to just balance the effect of a magnetic field of strength 1.8×10^{-3} N/amp·m?
b) what voltage must be supplied to the electric deflecting plates to produce the electric field strength of part (a) of this problem if the plates are 0.10 m apart?
c) what will happen to the α particles of problem 21.2 (b) moving through the crossed magnetic and electric fields of this problem?

21.5 For each part below, select the most appropriate radiation(s): α, β, or γ.

a) most penetrating radiation
b) most easily absorbed by aluminum foil
c) most strongly ionizing radiation
d) may require thick "radiation shields" for protection
e) cannot be deflected by a magnet
f) largest radius of curvature when travelling across a magnetic field
g) highest q/m value
h) important in Rutherford's and Royd's "mousetrap" experiment
i) involved in the transmutation of radium to radon
j) involved in the transmutation of bismuth 210 to polonium 210

21.6 Suggest an explanation for the following observations:

a) The Curies noticed in 1899 that nonradioactive substances placed near a radium compound appeared to become radioactive.
b) William Crookes discovered in 1900 that, when a strongly radioactive uranium-containing compound was purified chemically, the uranium compound itself was left with a much smaller activity, and the separate residue containing none of the uranium was strongly radioactive.

c) Becquerel found, in 1901, that in a case like (b) the uranium compound regained its original activity after several months while the residue gradually lost most of its activity during the same time.

21.7 A Geiger counter shows that the rate of emission of β particles from an initially pure sample of a radioactive substance decreases to one-half the initial rate in 25 hours.

a) What fraction of the original number of radioactive atoms is still unchanged at that time?
b) What fraction of the original number will have disintegrated in 50 hours?
c) What assumptions have you made in giving these answers? How might you check them?

21.8 Suppose at time t_o a sample of pure radium consisted of 2.66×10^{21} atoms. (The half-life of radium is approximately 1600 years.)

a) If N_t is the number of radium atoms in the sample at a time t, make a graph of N_t vs. time covering a period of 8000 years.
b) Show that at the end of 8000 years, 8.3×10^{19} radium atoms still remain in the sample.
c) From your graph, estimate the number of radium atoms in the sample after 4000 years.

21.9 The cylinder in the beaker shown and described on p. 19 reportedly contained "17,000 curies" of cobalt 60. A curie is defined as 3.70×10^{10} disintegrations per second.

a) How much energy is released per disintegration in the cobalt 60?
b) What would be the rate of heat production of that cylinder after 15 years? (The half-life of cobalt 60 is approximately 5 years.)

21.10 Radioactive isotopes in quantities of 10 micro-curies or less can be purchased from the U.S. Atomic Energy Commission. How many disintegrations per second occur in a 10 micro-curie sample?

21.11 Plot the counting rate as a function of time and determine the approximate half-life of the substance having the following disintegration rates (counting rates):

Time (hr)	Counting rate (counts/min)	Time (hr)	Counting rate (counts/min)
0.0	....	6.0	1800
0.5	9535	7.0	1330
1.0	8190	8.0	980
1.5	7040	9.0	720
2.0	6050	10.0	535
3.0	4465	11.0	395
4.0	3300	12.0	290
5.0	2430		

How many atoms decay each minute for each 10^6 atoms in the sample? (Use the relationship $\lambda T = 0.693$ derived on p. 26.) Does this number remain constant?

21.12 It takes 10 years for 10 per cent of the atoms of a fresh sample of radioactive substance to decay. How much of the 90 per cent that is left will decay in the next 10 years?

Chapter 22 Isotopes

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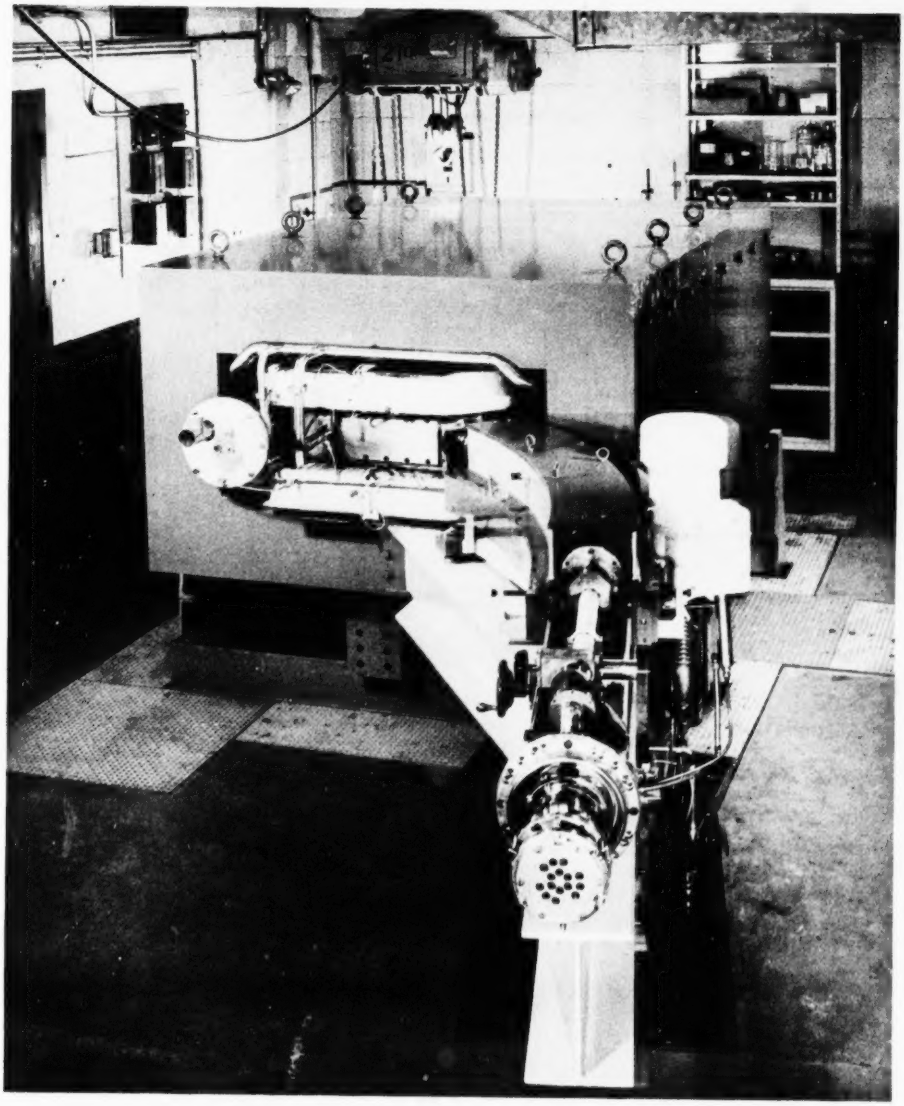


Partially assembled mass spectrograph in the laboratory of K.T. Bainbridge at Harvard University.

22.1 The concept of isotopes. The discovery that there are three radioactive series, each containing apparently new elements, raised a serious problem. In 1910 there were some empty spaces in the periodic table of the elements but there were not enough spaces for the many new elements. The periodic table represents an arrangement of the elements according to their chemical properties and, if it were unable to include the radioactive elements, it would have to be revised, perhaps in some drastic and fundamental way.

Soddy suggested a solution that threw a flood of light on the nature of matter and on the periodic law of the elements. The clue to the puzzle lay in the observation that some of the supposedly new elements had chemical properties identical with those of well-known elements, although some of their physical properties were different. For example, the "great-granddaughter" of uranium was found to have the same chemical properties as uranium itself. The two could not be separated by chemical means; no chemist had detected, by chemical analysis, any difference between these two substances. But they do differ from each other in certain physical properties. They are now known to be two different forms of uranium—uranium 238 and uranium 234, respectively. As Table 21.1 shows, uranium 238 and 234 have quite different half-lives: 4.5×10^9 years and 2.5×10^5 years, respectively; and the mass of a uranium 234 atom must be smaller than that of a uranium 238 atom by the mass of one α particle and two β particles. Another pair of radioactive substances, radium B and radium G, were found to have the same chemical properties as lead: when mixed with lead they could not be separated from it by chemical means. These substances are now known as lead 214 and lead 206, respectively. But lead 214 is radioactive and lead 206 is stable, and Table 21.1 shows that they must differ in mass by the mass of two α particles and four β particles. There are many other examples of such differences.

Soddy proposed that a chemical element could be regarded as a pure substance only in the sense that all of its atoms have the same chemical properties. He suggested that a chemical element may in fact be a mixture of atoms some of which have different radioactive behavior and different atomic masses but the same chemical properties. This idea meant that one of the basic postulates of Dalton's atomic theory would have to be changed, namely the postulate that the atoms of a pure element are alike in all respects. According to Soddy, it is only in chemical properties that the atoms of a given element are identical. The several physically different species of atoms making up a particular element occupy the same place in the periodic table, that is, have the same atomic number Z. Soddy called them isotopes of the element, from the Greek isos and topos meaning same and place (same place in the periodic table). Thus uranium 238 and uranium 234 are isotopes of uranium; lead 214 and lead 206 are isotopes of lead. SG 22.1

The many species of radioactive atoms in the three radioactive series were shown by chemical analysis to be isotopes of one or another of the last eleven elements in the periodic table—from lead to uranium. For example, the second and fifth members of the uranium series were shown to be isotopes of thorium, with Z = 90; the 8th, 11th and 14th members turned out to be isotopes of polonium (Z = 84). The old symbols were therefore rewritten to represent both the chemical similarity and physical difference among isotopes. The present names, for example, are uranium 238 and uranium 234, shown in Table 21.1.

Q1 **Why wasn't it necessary to expand the periodic table to fit in the newly discovered radioactive substances?**

22.2 Transformation rules. Two questions then arose: how do changes in chemical nature come about in radioactive decay; and, more specifically, what determines whether the atomic number Z increases or decreases in a radioactive transformation?

In 1913, the answers to these questions were given independently by Soddy in England and by A. Fajans in Germany. They each proposed two rules we will call the transformation rules of radioactivity. Recall that by 1913 Rutherford's nuclear model of the atom was generally accepted. Using this model, one could consider a radioactive atom to have an unstable nucleus which emits an α or β particle. Every nucleus has a positive charge $+Zq_e$, where Z is the atomic number and q_e is the magnitude of the charge of an electron. The nucleus is surrounded by Z electrons which make the atom as a whole electrically neutral and determine the chemical behavior of the atom. An α particle has an atomic mass of about 4 units and a positive charge of 2 units, $+2q_e$. A β particle has a negative charge of one unit, $-q_e$, and very little mass.

The transformation rules may now be stated as follows:

(1) When a nucleus emits an α particle, the mass of the atom decreases by 4 atomic mass units and the atomic number Z of the nucleus decreases by 2 units; the resulting atom belongs to an element two spaces back in the periodic table.

Example:

$_{84}Po^{218} \longrightarrow {}_{82}Pb^{214} + \alpha$.

(2) When a nucleus emits a β particle, the mass of the atom is practically unchanged, but the atomic number Z increases by one unit; the resulting atom belongs to an element one place forward in the periodic table. When a γ ray is emitted, there is, of course, no change in the number of atomic mass units or the atomic number.

Example:

$_{82}Pb^{214} \longrightarrow {}_{83}Bi^{214} + \beta.$

Table 21.1 shows that these rules apply to the uranium-radium series so far as the atomic number is concerned. The Rutherford-Bohr model of the atom shows why a change in chemical nature occurs as a result of α or β emission. An α particle takes two positive charges from the nucleus, and the resulting new atom can hold two fewer electrons than before in its outer shells. The new atom acts chemically like an atom of an element with an atomic number two units less than that of the atom before the radioactive change occurred. In β emission, the nucleus becomes more positively charged, by one unit. The number of electrons around the nucleus increases by one and the atom acts chemically like an atom with an atomic number one unit greater than that of the atom before the radioactive change occurred.

By using the transformation rules Soddy and Fajans were able to assign places in the periodic table to all of the radioactive elements. Each of these elements fell into a place appropriate to its chemical properties so that no revision of the periodic table was needed. Many of the positions (determined by atomic number) between Z = 82 (lead) and Z = 92 (uranium) now contained several isotopes. These results were consistent with the hypothesis of the existence of isotopes, but direct, independent evidence was also sought—and it was obtained in 1914.

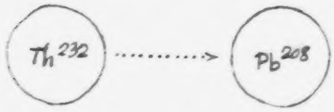
SG 22.2

Q2 **By how many units does the mass of an atom change during α decay? During β decay?**

Q3 **By how many units does the charge of a nucleus change during α decay? During β decay?**

22.3 Direct evidence for isotopes of lead. Soddy knew that the stable end product of the uranium-radium series had the chemical properties of lead, and that the end product of the thorium series also had the chemical properties of lead. But he saw that these end products should have atomic masses different from that of ordinary lead (that is, lead that was not produced from a radioactive series). This result follows from a simple calculation of the change in mass as an atom decays from the starting point of a radioactive series to the end point. The calculation is simplified by ignoring beta decays in which no appreciable change in mass is involved.

22.3



In the uranium series 8 α particles, each with atomic mass of 4 units, are emitted. Hence, the end product of the series is expected to have an atomic mass close to 238 - (8 × 4) = 206 units. In the thorium series, the end product comes from thorium 232, with an atomic mass of about 232 units, and 6 α particles are emitted along the way. It should therefore have an atomic mass close to 232 - (6 × 4) = 208 units. The atomic mass of ordinary lead was known from chemical analysis to be 207.2 units. The lead extracted from the mineral thorite, which consists mainly of thorium and contains only one or two per cent by mass of uranium may be presumed to be the final product of the thorium series. The atomic mass of lead extracted from thorite should therefore be significantly different from the atomic mass of lead extracted from a uranium mineral such as pitchblende, and from the atomic mass of ordinary lead.

Here was a quantitative prediction which could be checked, and a number of chemists in Scotland, France, Germany, Austria and the United States attacked the problem. At Harvard University, T. W. Richards found atomic masses as low as 206.08 for samples of lead from ores rich in uranium. Chemists in Austria found samples of lead, in the ore uraninite, with an atomic mass of 206.04. Soddy and others found samples of lead from thorite with atomic masses as high as 207.8 and 207.9. The results left no doubt that uranium was transformed into a light isotope of lead, and thorium into a heavier isotope of lead, and that both isotopes have atomic masses different from that of ordinary lead (207.2).

Frederick Soddy (1877-1956), an English chemist, studied at Oxford, and went to Canada in 1899 to work under Rutherford at McGill University in Montreal. There the two worked out their explanation of radioactive decay. Soddy returned to England in 1902 to work with Sir William Ramsay, the discoverer of the rare gases argon, neon, krypton and xenon. Ramsay and Soddy showed, in 1903, that helium was continually produced by naturally radioactive substances. In 1921, Soddy was awarded the Nobel Prize in chemistry for his discovery of isotopes. He was a professor of chemistry at Oxford from 1919 to 1936.

Richards and his co-workers also found important similarities between ordinary lead and lead 206. The densities of these two isotopes turned out to be proportional to the respective atomic masses, which implied that the atoms of lead 206 and ordinary lead had the same volume. Furthermore, lead 206 and ordinary lead were found to have the same optical spectrum; their compounds had the same solubility in water, and the crystals of their nitrates had the same index of refraction. Hence, lead 206 and ordinary lead were shown to have properties as similar as Soddy had predicted and as Bohr's theory suggested they should be. Together, all of these results meant that the theories of radioactivity and atomic structure that were emerging in the early years of the twentieth century had passed a demanding test, and the confidence that physicists and chemists had in these theories was greatly increased.

The three forms of lead which were compared in the studies discussed so far, that is, ordinary lead, lead 206 (from uranium) and lead 208 (from thorium) were all stable—not radioactive. The question immediately arose whether *other* stable elements are really mixtures of isotopes. In Soddy's words:

> Naturally the question was asked whether any of the common elements, for which radioactive methods of analysis are not available, are, as supposed, really homogeneous elements; and whether any are mixtures of different isotopes, with different atomic masses but with identical chemical properties, so merely appearing to be homogeneous under chemical analysis.

There are four naturally occurring lead isotopes: $_{82}Pb^{204}$, and the end products of three decay chains:

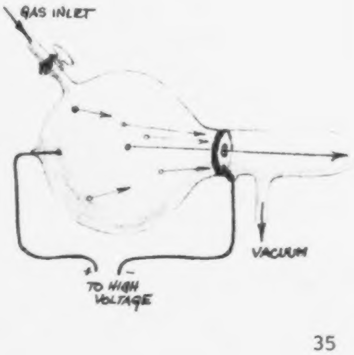
$_{82}Pb^{206}$, from uranium;
$_{82}Pb^{207}$, from actinium;
$_{82}Pb^{208}$, from thorium.

Q4 How were the different atomic masses of lead decay-products predicted?

22.4 *Positive rays*. It was hard to show that stable elements may be mixtures of isotopes because isotopes cannot be separated by ordinary chemical methods. Any attempt to separate a pair of isotopes must depend on a difference in some property which depends, in turn, on the difference between their atomic masses. However, except for the very lightest elements, the difference in atomic mass is small compared to the atomic masses themselves. For the lead isotopes discussed in the last section the difference was only two units in about 200 units, or about one per cent. Any difference in a physical property between two isotopes having such a small mass difference would be expected to be very small, making separation difficult to achieve. Fortunately, when the question of the possible existence of isotopes of stable elements arose, a method was available which could answer the question. This method, developed by J. J. Thomson and extended by A. J. Dempster and others, depended on the behavior of positively charged ions when these are traveling in electric and magnetic fields.

In a cathode ray tube, the electrons emitted from the cathode ionize the atoms of gas with which they collide. It was thought that the positive ions produced would accelerate toward the cathode and be neutralized there. In 1886, the German physicist Goldstein found that if holes are made in the cathode, rays pass through the cathode and emerge beyond it. Fig. 22.1 is a schematic diagram of a discharge tube for producing such rays. If the cathode fits the tube tightly, so that no gas can enter the region behind it, and if the holes are so small that very little gas can get through them, a high vacuum can be produced on the side where the rays emerge. The rays then have quite a long range and can be deflected by externally applied electric and magnetic fields.

Fig. 22.1 Discharge tube for producing a beam of positive ions. The gas between anode and cathode is ionized by the electric field. Positive ions are then accelerated toward the cathode where some of them pass through small holes and enter the well-evacuated region beyond.



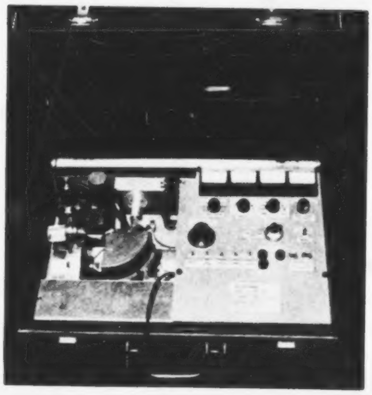
J. J. Thomson (1856-1940) at work in the Cavendish Laboratory.

From the direction of the deflections it was concluded that the rays consist of positively charged particles. The rays were therefore called "positive rays" and were thought (correctly) to consist of positively charged ions of the atoms or molecules of the residual gas remaining in the discharge tube after partial evacuation.

Thomson used the positive rays from different gases to determine the relative masses of the atoms of the gases. Rather than describe the details of Thomson's early apparatus we shall describe an improved type of instrument that is in common use. This instrument typically consists of two parts: the first part provides a beam of ions all moving with the same speed; in the second part the ions pass through a magnetic field, which deflects them from a straight path into several different curved paths determined by their relative masses. Ions of different mass are thus separated to such an extent that they can be detected separately. By analogy with the instrument that separates light of different wavelengths, the instrument that separates ions of different mass was called a mass spectrograph. Its operation is explained on the opposite page.

Thomson had obtained results from measurement of $\frac{q}{m}$ for positive rays which were quite different from those obtained for cathode ray particles or β particles. Both the speeds and $\frac{q}{m}$ were found to be smaller for gases with heavier molecules. These results are consistent with the idea that the positive rays are streams of positively ionized atoms or molecules.

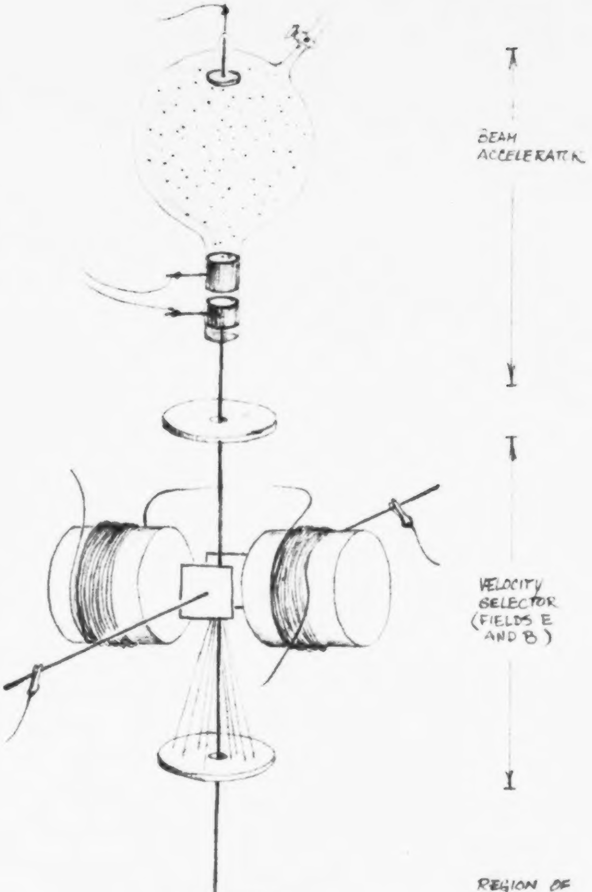
Can the values of q and m be separately determined? The magnitude of q must be a multiple of the electron charge q_e, that is, it can only be q_e, or $2q_e$, $3q_e$, $4q_e$,.... The greater the charge, the greater the magnetic force will be and, therefore, the more curved the path of the ions. In the apparatus of Fig. 22.2 a doubly ionized atom (an ion with charge $+2q_e$) will follow a path with half the radius of that of a singly ionized atom of similar type, a triply ionized atom will trace out a semi-circular path with one-third the radius, etc. Thus, for each type of atom analyzed, the path with the largest radius will be that taken by the ions with the single charge q_e. Since q is known for each path, the mass of the ions can be determined from the known values of q/m.



Some mass spectrometers are portable; small ones similar to this are carried aloft for analysis of the upper atmosphere.

The study of positive rays with the mass spectrograph made it possible to measure for the first time the masses of individual atoms. With the methods used before, it was possible to obtain only average masses for very large numbers of atoms.

Fig. 22.2 The principle of the mass spectrograph.


BEAM ACCELERATOR
VELOCITY SELECTOR (FIELDS E AND B)
REGION OF DEFLECTING FIELD B'
PHOTOGRAPHIC PLATE (OR ION CURRENT DETECTOR)

The magnetic separation of isotopes begins by electrically charging the atoms of a sample of material, for example by means of an electric discharge through a sample of gas. The resulting ions are then accelerated into a beam by an electric potential difference.

Before the different isotopes in the beam are separated, there is usually a preliminary stage that allows only those ions with a certain velocity to pass through. In one type, the ion beam initially enters a region of crossed magnetic fields $\vec{B}$ and $\vec{E}$, where each ion experiences a magnetic force of magnitude qvB and an electric force of magnitude qE. The magnetic and electric forces act on an ion in opposite directions, and only for ions of a certain speed will the forces be balanced, allowing them to pass straight through the crossed fields. For these ions $qvB = qE$, and so their speed $v = E/B$. Because only ions with this speed in the original direction remain in the beam, this part of the apparatus is called a velocity selector.

The separation of isotopes is then accomplished by a magnetic field B'. As the beam enters this field, the magnetic force acts as a centripetal force to cause each ion to move in a circular arc whose radius R depends upon the ion's charge-to-mass ratio. That is $qvB' = mv^2/R$ and so $q/m = v/B'R$.

The divided beams of ions fall on either a photographic plate (in a mass spectrograph) or a sensitive electrometer probe (in a mass spectrometer), allowing the radii of their deflections to be calculated from the geometry of the apparatus. Since v, B' and R can be determined from measurements; the charge-to-mass ratio of each velocity of ions in the beam can be calculated.

The uncertainty of mass determinations made with modern mass spectrographs can be less than one part in a hundred thousand, that is, less than 0.001 percent. The difference in the masses of the isotopes of an element is never less than about 0.3 percent, and so is easily detected.

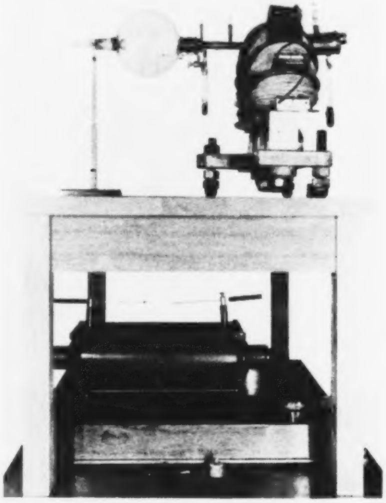
Q5 The curvature of an ion beam in a magnetic field depends on both the mass and speed of the ions. How then can a mass spectograph make precise separation by mass?

22.5 Separating Isotopes. In Thomson's original instrument the error was about one per cent, but this was small enough to permit Thomson to make the first observation of separated isotopes. He introduced a beam of neon ions from a discharge tube containing chemically pure neon into his mass spectrograph. The atomic mass of neon had been determined as 20.2 atomic mass units by means of the usual methods for determining the atomic (or molecular) mass of a gas. At about the position on the photographic plate where ions of atomic mass 20 were expected to arrive, a dark line was observed when the plate was developed. But, in addition, there was also present a faint line such as would indicate the presence of particles with atomic mass 22. No chemical element or gaseous compound was known which had this atomic or molecular mass. The presence of this line suggested, therefore, that neon might be a mixture of one form, or isotope, with atomic mass 20 and another isotope with atomic mass 22. The average chemical mass 20.2 would result if neon contained about ten times as many atoms of atomic mass 20 as of atomic mass 22.

Francis William Aston (1877-1945) studied chemistry at the University of Birmingham. In 1910 he went to Cambridge to work under J. J. Thomson. He was awarded the Nobel Prize in chemistry, in 1922, for his work with the mass spectrograph. In disagreement with Rutherford, Aston pictured a future in which the energy of the atom would be tapped by man. In his Nobel acceptance speech he also spoke of the dangers involved in such a possibility. Aston lived just long enough—by three months—to learn of the explosion of the nuclear bombs.

The evidence that neon has two isotopes was so striking that Thomson's associate, F. W. Aston, looked for further evidence that might bear on this problem. It was well known from kinetic theory that in a mixture of two gases with different molecular masses the lighter molecules have a higher average speed than the heavier molecules. The lighter molecules, therefore, collide more often with the walls of a container than do the heavier molecules. If the mixture is allowed to diffuse through a porous wall from one container into another, the heavier molecules are less likely to pass through than the lighter, faster ones. The gas that does not get through the wall will, therefore, have more of the heavier molecules than the gas that does pass through the wall.

Aston allowed part of a sample of chemically pure neon gas to pass through such a wall. One pass accomplished only a slight separation of the lighter and heavier molecules, so a portion of the gas which had passed through the wall was passed through the wall again, the process was repeated many times. He measured the atomic mass of each fraction of the gas and found values of 20.15 atomic mass units for the fraction that had passed through the wall many times and 20.28 units for the fraction that had been left behind many times. The difference in average atomic mass indicated that the neon was, indeed, a mixture of isotopes. Even more impressive was the change in the relative intensities of the two traces (for the masses 20 and 22) in the mass spectrograph. The line corresponding to mass 22 was more prominent in the analysis of the fraction of the gas that had been left behind, showing that this fraction was "enriched" in atoms of mass 22. Although the separation of the two isotopes was not complete, it was clear that there are two isotopes of neon, one with atomic mass 20, the other with atomic mass 22. The optical emission spectrum of the enriched sample was the same as that of the original neon sample—proving that no substance other than neon was present.



Side view of one of Aston's earlier mass spectrographs.

SG 22.3

These results encouraged Aston to improve the design of the mass spectrograph and determine the atomic masses of many elements. He found that other elements also were made up of isotopes. The atomic masses of the isotopes of the naturally occurring elements have now been determined. Figure 22.3 shows the mass spectrograph record obtained for germanium, indicating that this element has five isotopes. Pictures of this kind are called "mass spectra."

Although we cannot measure the mass of a neutral atom in a mass spectrograph (why not?), we usually list isotopic masses for neutral atoms.

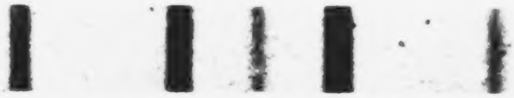


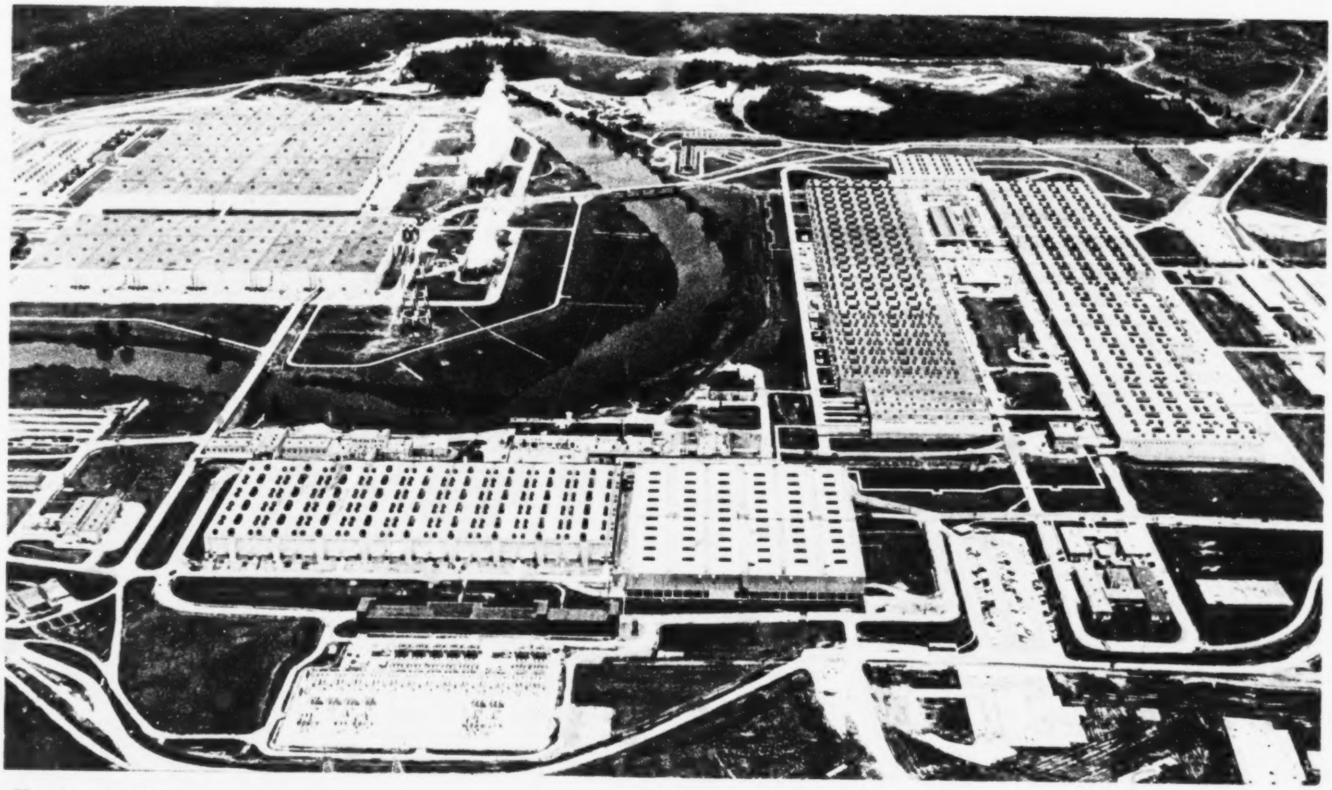
Fig. 22.3 The mass spectrum of germanium, showing the isotopes of mass numbers 70, 72, 73, 74, 76.

SG 22.4

Both the electromagnetic and gas-diffusion methods of separating isotopes have been modified for large-scale applications. The electromagnetic method is used by the United States Atomic Energy Commission to provide samples of separated isotopes for research. The method used by Aston in achieving a small degree of separation of the neon isotopes has been developed on an enormous scale to separate the isotopes of uranium in connection with the manufacture of nuclear bombs and the production of nuclear power.

Q6 What were 3 experimental results which supported the belief in two isotopes of neon?

Q7 Isotopes are separated in a mass spectograph because more massive ions are deflected less. Why are isotopos separated in diffusing through a porous wall?

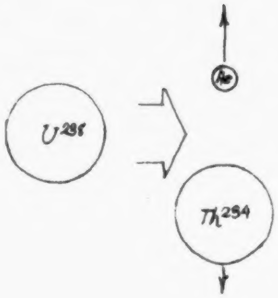


The Atomic Energy Commission's Gaseous Diffusion Plant at Oak Ridge, Tennessee. The long buildings right of center made up the first plant.

22.6 A useful notation for nuclides and nuclear reactions. It will be useful to summarize some ideas and notations. Because of the existence of isotopes it was no longer possible to designate an atomic species by means of the atomic number Z alone. To distinguish among the isotopes of an element some new symbols were introduced. One is the mass number, A, defined as the whole number closest to the measured atomic mass (see Table 22.1). For example, the lighter and heavier isotopes of neon are characterized by the pairs of values: $Z = 10$, $A = 20$, and $Z = 10$, $A = 22$, respectively. An element which consists of a single atomic species can, of course, also be characterized by its Z and A values. These values are determined by the properties of the atomic nucleus: according to the Rutherford-Bohr model of the atom, the atomic number Z is the magnitude of the positive charge of the nucleus in elementary charge units. The mass number A is very nearly equal to the atomic mass of the nucleus (expressed in atomic mass units) because the total electron mass is very small compared to the mass of the nucleus. The term nuclide is used to denote an atomic species characterized by particular values of Z and A. An isotope is then one of a group of two or more nuclides having the same atomic number Z but different mass numbers A. A radioactive atomic species is a radioactive nuclide, or radionuclide for short. A nuclide is usually denoted by the chemical symbol with a subscript at the lower left giving the atomic number, and a superscript at the upper right giving the mass number. In the symbol $_ZX^A$ for a nuclide, Z is the atomic number, X is the chemical symbol and A is the mass number. For example, $_4Be^9$ is the nuclide beryllium with atomic number 4 and mass number 9; the symbols $_{10}Ne^{20}$ and $_{10}Ne^{22}$ represent the neon isotopes discussed above. The Z-value is the same for all the isotopes of a given element (X), and so is often omitted—except when it is needed for balancing equations (as you will shortly see). Thus, we often write O^{16} for $_8O^{16}$, or Ne^{20} for $_{10}Ne^{20}$ or U^{238} for $_{92}U^{238}$.

The introduction of the mass number and the symbol for a nuclide makes it possible to designate the radioactive nuclides in an easy and consistent way, as was shown in Table 21.1. Radioactive decay can be expressed by a simple equation representing the changes that occur in the decay process. The first step in the uranium-radium series, the decay of uranium 238 into thorium 234, may be written:

$$_{92}U^{238} \xrightarrow{\text{decays into}} {}_{90}Th^{234} + {}_2He^4.$$



The symbol $_2He^4$ stands for the helium nucleus (α particle); the other two symbols represent the initial and final atomic nuclei, each with the appropriate charge and mass number. The equation represents a nuclear reaction, and is analogous to an equation for a chemical reaction. The atomic numbers on the two sides of the equation must balance because the electric charge of the nucleus must be conserved: $92 = 90 + 2$. Also, the mass numbers must balance because of conservation of mass: $238 = 234 + 4$. We see from Table 21.1 that $_{90}Th^{234}$ (thorium 234) decays to $_{91}Pa^{234}$ (protactinium 234) with the emission of a β particle. Since a β particle (electron) has charge $-q_e$ and has an extremely small mass, the symbol $_{-1}e^0$ is used for it. This β decay process may then be represented by the equation:

$$_{90}Th^{234} \xrightarrow{\text{decays into}} {}_{91}Pa^{234} + {}_{-1}e^0 + \bar{\nu}$$

There is also an antineutrino ($\bar{\nu}$) given off together with the β particle. The neutrino and antineutrino are two particles which will be discussed briefly in Sec. 23.6.

SG 22.5

SG 22.6

SG 22.7

SG 22.8

Q8 Write the complete symbol for the nuclide with atomic mass 194 and atomic number 78. Of what element is it an isotope?

Q9 Complete the following equation for α-decay:

$$_ZX^A \longrightarrow {}_2He^4 + {}_{Z-2}X^?$$

Q10 Complete the following equation for β-decay:

$$_ZX^A \longrightarrow {}_{-1}e^0 + {}_?X^A$$

Table 22.1 Relative natural abundances and masses of some nuclides

The masses are given in atomic mass units (amu) based on ${}_6C^{12}$ = 12.000 000

Element	Chemical Symbol	Atomic Number Z	Mass Number A	Relative Abundance %	Mass of Neutral Atom (amu)
Hydrogen	H	1	1	99.98	1.007825
		1	2	0.02	2.014102
Helium	He	2	4	100.00	4.002604
Lithium	Li	3	6	7.42	6.015126
		3	7	92.58	7.016005
Beryllium	Be	4	9	100.00	9.012186
Carbon	C	6	12	98.89	12.000000
		6	13	1.11	13.003354
Nitrogen	N	7	14	99.63	14.003074
		7	15	0.37	15.000108
Oxygen	O	8	16	99.76	15.994915
		8	17	0.04	16.999134
		8	18	0.20	17.999160
Neon	Ne	10	20	90.92	19.992440
		10	21	0.26	20.993849
		10	22	8.82	21.991385
Aluminum	Al	13	27	100.00	26.981535
Chlorine	Cl	17	35	75.53	34.968855
		17	37	24.47	36.965896
Platinum	Pt	78	190	0.01	189.9600
		78	192	0.78	191.9614
		78	194	32.90	193.9628
		78	195	33.80	194.9648
		78	196	25.30	195.9650
		78	198	7.21	197.9675
Gold	Au	79	197	100.00	196.9666
Lead	Pb	82	204	1.50	203.9731
		82	206	23.60	205.9745
		82	207	22.60	206.9759
		82	208	52.30	207.9766
Thorium	Th	90	232	100.00	232.0382
Uranium	U	92	234	0.006	234.0409
		92	235	0.720	235.0439
		92	238	99.274	238.0508

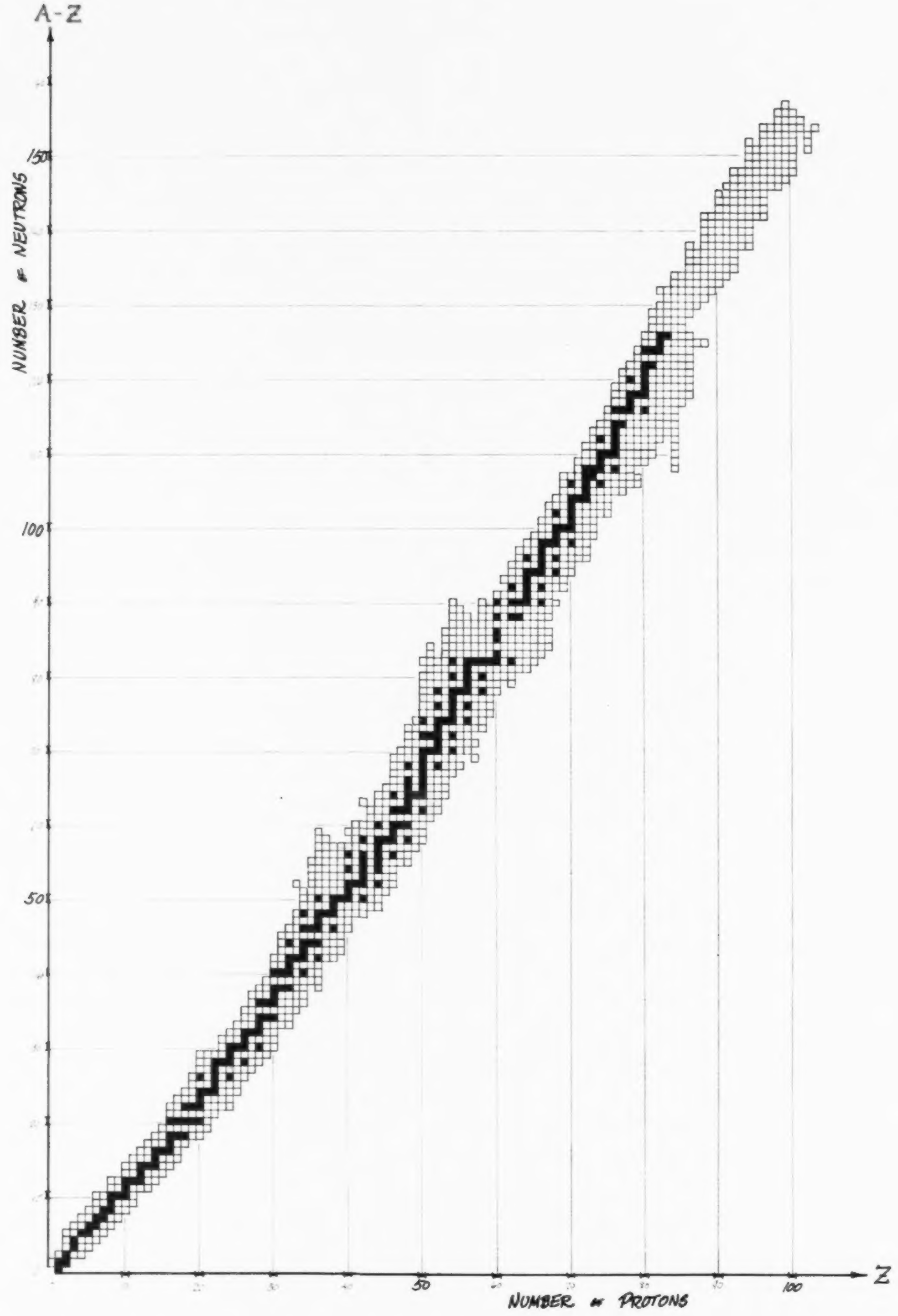
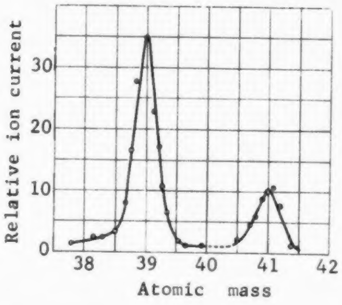


Chart of the known nuclides. Each black square represents a stable nuclide, each open square represents an unstable nuclide. All isotopes of a given element are found in a vertical column centered on the element's atomic number Z. (As will be seen in the next chapter, the Z number is the number of protons in the nucleus, and A - Z, the difference between the atomic mass and atomic number, is the number of neutrons.)

22.7 The stable isotopes of the elements and their relative abundances. Mass spectra, such as the one of germanium shown in Fig. 22.3 have been determined for all the elements with at least one stable nuclide. These are the elements with atomic numbers between 1 (hydrogen) and 83 (bismuth). A few of the results are listed in Table 22.1. The table also includes the unstable (radioactive) elements uranium and thorium because they have such long half-lives that they are still present in large quantities in some rocks. Uranium has three naturally occurring isotopes, one of which, U^{235}, has remarkable nuclear properties that have made it important in military and political affairs as well as in science and industry. As can be seen in Table 22.1, the relative abundance of U^{235} is very low and it must first be separated from the far more abundant U^{238} before it can be used in practical applications. Such applications and some of their social effects will be discussed in Chapter 24.



Detection of the isotopes of potassium in a mass spectrometer. In a mass spectrometer the current due to the ions is detected. Comparison of the current due to each isotope permits fairly precise estimates of the relative abundances of the isotopes.

Of the elements having atomic numbers between 1 and 83, only about one-fourth of them are single species, the others all have two or more isotopes. As a result, the 83 elements actually consist of 284 naturally occurring nuclides. All but 25 of these nuclides are stable. Many elements have only one stable nuclide, others have several and tin has the greatest number, ten. Carbon and nitrogen each have two and oxygen has three. (Table 22.1 shows that the isotope O^{16} has a very high relative abundance; the isotopes O^{17} and O^{18} being relatively rare.)

The 25 naturally occurring unstable nuclides show a very small degree of radioactivity; they are not associated with the decay chains of the heavy radionuclides and have activities which are generally much feebler. The most common of these light nuclides is $_{19}K^{40}$, an isotope of potassium that has a relative abundance of only 0.012%. This isotope, which emits β particles, has a long half-life (1.3×10^9 years) which makes it extremely useful for determining the ages of certain rocks. Such information, coupled with information on the decay of U^{238}, can be used to estimate the age of the earth.

SG 22.9

Hydrogen, the lightest element, has two stable isotopes, of which the heavier one, with mass number 2, has a relative abundance of only 0.02%. The hydrogen isotopes are exceptional in that the rare isotope has an atomic mass twice that of the common isotope. As a result, the differences between the properties of the two isotopes are more marked than in any other pair of isotopes. The hydrogen isotope of mass 2 has therefore been given its own name, deuterium, with the symbol D; sometimes it is called "heavy hydrogen." There is a kind of water, called "heavy water" or "deuterium oxide," with the formula $({}_1H^2)_2O$ or D_2O. Heavy water differs from ordinary water in some important respects: its density is 1.11 gram per cm^3 as compared with 1.00 for ordinary water; it freezes at 3.82°C and boils at 101.42°C, the corresponding temperatures for ordinary water being 0°C and 100°C, respectively. Naturally occurring water contains only about 1 atom of H^2 per 7000 atoms of H^1, but methods have been developed for producing nearly pure D_2O in large amounts. Heavy water is important in some types of devices for the controlled release of nuclear energy, as will be explained in Chapter 24.

H. C. Urey received the 1934 Nobel Prize in chemistry for his discovery of "heavy" hydrogen.

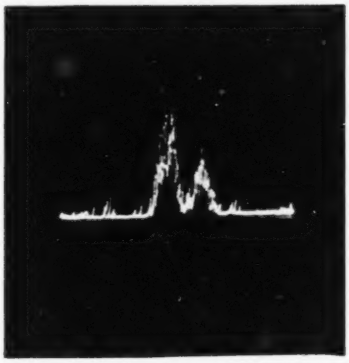
Some interesting and important regularities have been found among the natural abundances. The number of nuclides with the various combinations of even and odd values of Z and A are listed in Table 22.2. It is evident that nuclides with even Z and even A are much more numerous than those with any other combination. Elements with even Z have, on the average, more isotopes per element than those with odd Z. Any theory of the nucleus will have to account for these regularities, which are related to the stability of atomic nuclei. Information of this kind is analogous to observations of the positions of planets, to data on chemical compounds and to atomic spectra. All of these provide material for the building of theories and models.

Table 22.2 Some Interesting Data Concerning Nuclides

	Number of Stable Elements	Number of Nuclides			Avg. Number of Isotopes Per Element
		with Odd A	with Even A	Total	
Odd Z	40	53	8	61	1.5
Even Z	43	57	166	223	5.2
Total	83	110	174	284	3.4

Q11 What is deuterium?

Q12 Neon actually has three isotopes (see Table 22.1). Why did Thomson and Aston find evidence for only two isotopes?



This is a photograph of the oscilloscope display of a high-resolution mass spectrometer. The high peak, on the left, indicates the He^3 isotope of mass 3.016030 amu. The other peak indicates H^3, the extra heavy hydrogen isotope, otherwise known as tritium, whose mass is 3.016049 amu. The mass difference is therefore about one part in 150,000.

22.8 Atomic masses. The masses of most of the stable nuclides have been determined and the results are of fundamental importance in quantitative work in nuclear physics and its applications. The standard of mass adopted by physicists for expressing the atomic mass of any nuclide was slightly different from that used by chemists for the chemical atomic weights. The chemists' scale was defined by assigning the value 16.0000 atomic mass units to ordinary oxygen. But, as can be seen in Table 22.1, oxygen is a mixture of three isotopes, two of which, O^{17} and O^{18}, have very small abundances. For isotopic mass measurements, the value 16.0000 was assigned to the most abundant isotope, O^{16}, and this mass was used as the standard by physicists. For some years, up to 1960, the atomic mass unit, 1 amu, was defined as 1/16 of the mass of a neutral O^{16} atom. Since 1960, $_8O^{16}$ has been replaced by $_6C^{12}$ as the standard, and the atomic mass unit is now defined by both physicists and chemists as 1/12 of the mass of a neutral C^{12} atom. The main reason for the choice of carbon is that mass-spectrographic measurements of atomic masses are much more accurate than the older chemical methods. Carbon forms an exceptional variety of compounds, from light to very heavy, which can be used as comparison standards in the mass spectrograph.

SG 22.10

SG 22.11

The results obtained for the atomic masses of some elements of special interest are listed in Table 22.1. Atomic masses can be determined with great accuracy and, when expressed in atomic mass units, all turn out to be very close to integers. The mass differs from an integer by less than 0.06 amu for each nuclide. This result is known as Aston's whole-number rule and provides the justification for using the mass number in the symbol $_ZX^A$ for a nuclide or atom. The physical basis for this rule is connected with the structure of the nucleus and will be discussed in the next chapter.

Q13 **What nuclide is the current standard for atomic mass?**

List of the Elements

Element	Symbol	Atomic Number	Year of Isolation or Discovery and Origin of Name*
Actinium	Ac	89	1900 Greek aktis, ray
Aluminum	Al	13	1825 Latin alumen, substance with astringent taste
Americium	Am	95	1944 America
Antimony	Sb	51	15th century, Greek antimonos, opposite to solitude
Argon	Ar	18	1894 Greek argos, inactive
Arsenic	As	33	13th century, Greek arsenikon, valiant
Astatine	At	85	1940 Greek astatos, unstable
Barium	Ba	56	1808 Greek barys, heavy
Berkelium	Bk	97	1949 Berkeley, California
Beryllium	Be	4	1797 mineral, beryl
Bismuth	Bi	83	15th century, German weisse masse, white mass
Boron	B	5	1808 Arabic bawraq, white
Bromine	Br	35	1826 Greek bromos, a stench
Cadmium	Cd	48	1817 Latin cadmia, calamine, a zinc ore
Calcium	Ca	20	1808 Latin calcis, lime
Californium	Cf	98	1950 State & University of California
Carbon	C	6	prehistoric, Latin carbo, coal
Cerium	Ce	58	1804 the asteroid Ceres discovered 1803
Cesium	Cs	55	1860 Latin caesius, sky blue
Chlorine	Cl	17	1808 Greek chloros, grass green
Chromium	Cr	24	1797 Greek chroma, color
Cobalt	Co	27	1735 Greek kobolos, a goblin
Copper	Cu	29	prehistoric, Latin cuprum, copper
Curium	Cm	96	1944 Marie and Pierre Curie
Dysprosium	Dy	66	1886 Greek dysprositos, hard to get at
Einsteinium	Es	99	1952 Albert Einstein
Erbium	Er	68	1843 Ytterby, a town in Sweden
Europium	Eu	63	1900 Europe
Fermium	Fm	100	1953 Enrico Fermi
Fluorine	F	9	1886 Latin fluere, to flow
Francium	Fr	87	1939 France
Gadolinium	Gd	64	1886 Johan Gadolin, Finnish chemist
Gallium	Ga	31	1875 Gaul, or France
Germanium	Ge	32	1886 Germany
Gold	Au	79	prehistoric, Anglo-Saxon gold, symbol from Latin aurum
Hafnium	Hf	72	1922 Hafnia, Latin for Copenhagen
Helium	He	2	1895 Greek helios, the sun
Holmium	Ho	67	1879 Holmia, Latin for Stockholm
Hydrogen	H	1	1766 Greek hydro genes, water former
Indium	In	49	1863 indigo-blue spectrum line
Iodine	I	53	1811 Greek iodes, violet-like
Iridium	Ir	77	1804 Latin iridis, rainbow
Iron	Fe	26	prehistoric, Anglo-Saxon iren or isen, symbol from Latin ferrum
Krypton	Kr	36	1898 Greek kryptos, hidden
Lanthanum	La	57	1839 Greek lanthanien, to be concealed
Lawrencium	Lw	103	1961 Ernest O. Lawrence, inventor of cyclotron
Lead	Pb	82	Prehistoric, middle English led, symbol from Latin plumbum
Lithium	Li	3	1817 Greek lithos, stone
Lutetium	Lu	71	1905 Lutetia, ancient name of Paris
Magnesium	Mg	12	1774 Latin magnes, magnet
Mendelevium	Md	101	1955 Dmitri Mendeleev, who devised first Periodic Table
Mercury	Hg	80	prehistoric, Latin Mercurius, the god and planet
Molybdenum	Mo	42	1782 Greek molybdos, lead
Neodymium	Nd	60	1885 Greek neos, new, and didymos, twin
Neon	Ne	10	1898 Greek neos, new
Neptunium	Np	93	1940 planet Neptune
Nickel	Ni	28	1750 German Nickel, a goblin or devil
Niobium	Nb	41	1801 Niobe, daughter of Tantalus
Nitrogen	N	7	1772 Latin nitro, native soda, and gen, born
Nobelium	No	102	1957 Alfred Nobel
Osmium	Os	76	1804 Greek osme, a smell, from the odor of its volatile tetroxide
Oxygen	O	8	1774 Greek oxys, sharp, and gen, born
Palladium	Pd	46	1803 planetoid Pallas, discovered 1801
Phosphorus	P	15	1669 Greek phosphoros, light bringer
Platinum	Pt	78	1735 Spanish plata, silver
Plutonium	Pu	94	1940 Pluto, the second trans-Uranus planet

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*adapted from Alfred Römer, The Restless Atom, Science Study Series, Doubleday Co., N.Y.

Polonium	Po	84	1898	Poland, country of discoverer
Potassium	K	19	1807	English potash, symbol Latin kalium
Praseodymium	Pr	59	1885	Greek praseos, leek green, and didymos, a twin
Promethium	Pm	61	1947	Prometheus, fire bringer of Greek mythology
Protactinium	Pa	91	1917	Greek protos first, and actinium because it disintegrates into it
Radium	Ra	88	1898	Latin radius, ray
Radon	Rn	86	1900	because it comes from radium
Rhenium	Re	75	1924	Latin Rhenus, Rhine province of Germany
Rhodium	Rh	45	1804	Greek rhodon, a rose
Rubidium	Rb	37	1860	Latin rubidus, red
Ruthenium	Ru	44	1845	Latin Ruthenia, Russia
Samarium	Sm	62	1879	Samarski, a Russian engineer
Scandium	Sc	21	1879	Scandinavian peninsula
Selenium	Se	34	1817	Greek selene, moon
Silicon	Si	14	1823	Latin silex, flint
Silver	Ag	47	prehistoric,	Anglo-Saxon seolfor, symbol from Latin argentum
Sodium	Na	11	1807	Medieval Latin soda, symbol from Latin natrium
Strontium	Sr	38	1808	town of Strontian, Scotland
Sulfur	S	16	prehistoric,	Latin sulphur
Tantalum	Ta	73	1802	Tantalus of Greek mythology
Technetium	Tc	43	1937	Greek technetos, artificial
Tellurium	Te	52	1782	Latin tellus, the earth
Terbium	Tb	65	1843	Ytterby, town in Sweden
Thallium	Tl	81	1862	Greek thallos, a young shoot
Thorium	Th	90	1819	Scandinavian mythology, Thor
Thulium	Tm	69	1879	Latin Thule, most northerly part of the habitable world
Tin	Sn	50	prehistoric,	origin of name unknown, symbol Latin stannum
Titanium	Ti	22	1791	Greek mythology, Titans, first sons of the earth
Tungsten	W	74	1783	Swedish tung sten, heavy stone, symbol from the mineral wolframite
Uranium	U	92	1789	Planet Uranus
Vanadium	V	23	1830	goddess Vanadis of Scandinavian mythology
Xenon	Xe	54	1898	Greek xenos, strange
Ytterbium	Yb	70	1905	Ytterby a town in Sweden
Yttrium	Y	39	1843	Ytterby a town in Sweden
Zinc	Zn	30	prehistoric,	German Zink, akin to Zinn, tin
Zirconium	Zr	40	1824	Arabian Zerk, a precious stone

Periodic Table of the Elements

Group→ Period ↓	I	II											III	IV	V	VI	VII	0
1	1.0080 H 1																	4.0026 He 2
2	6.939 Li 3	9.012 Be 4											10.811 B 5	12.011 C 6	14.007 N 7	15.999 O 8	18.998 F 9	20.183 Ne 10
3	22.990 Na 11	24.31 Mg 12											26.98 Al 13	28.09 Si 14	30.97 P 15	32.06 S 16	35.45 Cl 17	39.95 Ar 18
4	39.10 K 19	40.08 Ca 20	44.96 Sc 21	47.90 Ti 22	50.94 V 23	52.00 Cr 24	54.94 Mn 25	55.85 Fe 26	58.93 Co 27	58.71 Ni 28	63.54 Cu 29	65.37 Zn 30	69.72 Ga 31	72.59 Ge 32	74.92 As 33	78.96 Se 34	79.91 Br 35	83.80 Kr 36
5	85.47 Rb 37	87.62 Sr 38	88.91 Y 39	91.22 Zr 40	92.91 Nb 41	95.94 Mo 42	(99) Tc 43	101.07 Ru 44	102.91 Rh 45	106.4 Pd 46	107.87 Ag 47	112.40 Cd 48	114.82 In 49	118.69 Sn 50	121.75 Sb 51	127.60 Te 52	126.9 I 53	131.30 Xe 54
6	132.91 Cs 55	137.34 Ba 56	* 57–71	178.49 Hf 72	180.95 Ta 73	183.85 W 74	186.2 Re 75	190.2 Os 76	192.2 Ir 77	195.09 Pt 78	196.97 Au 79	200.59 Hg 80	204.37 Tl 81	207.19 Pb 82	208.98 Bi 83	210 Po 84	(210) At 85	222 Rn 86
7	(223) Fr 87	226.05 Ra 88	† 89															

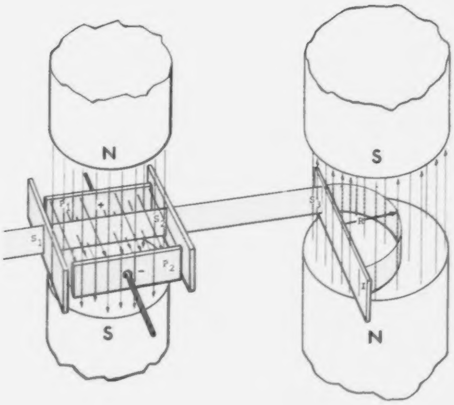
*Rare-earth metals	138.91 La 57	140.12 Ce 58	140.91 Pr 59	144.27 Nd 60	(147) Pm 61	150.35 Sm 62	151.96 Eu 63	157.25 Gd 64	158.92 Tb 65	162.50 Dy 66	164.93 Ho 67	167.26 Er 68	168.93 Tm 69	173.04 Yb 70	174.97 Lu 71
† Actinide metals	227 Ac 89	232.04 Th 90	231 Pa 91	238.03 U 92	(237) Np 93	(242) Pu 94	(243) Am 95	(245) Cm 96	(249) Bk 97	(249) Cf 98	(253) E 99	(255) Fm 100	(256) Mv 101	(253) No 102	(257) Lw 103

22.1 Soddy's proposal of isotopes meant that not all atoms of the same element are identical. Explain why this proposal does not require that the atoms of a given element show differences in chemical behavior.

22.2 After Soddy's proposal of isotopes, how could one go about determining whether an apparently new element was really new and should be given a separate place in the periodic table, or was simply an isotope of an already known element?

22.3 At the National Bureau of Standards, in 1932, a gallon of liquid hydrogen was slowly evaporated until only about 1 gram remained. This residue allowed the first experimental check on the existence of the "heavy" hydrogen isotope H^2.

a) With the help of the kinetic theory of matter, explain why the evaporation should leave a residue with an increased concentration of the isotope of greater atomic mass.
b) Why should the evaporation method be especially effective with hydrogen?



22.4 A mass spectrograph similar to that shown in the margin causes singly charged ions of chlorine 37 to travel a semi-circular path 1.000 meter in diameter and then strike a photographic plate.

a) How far apart will the traces of Cl^{37} and Cl^{35} be on the photographic plate?
b) What would be the diameter of the orbit of lead 208 ions if the same electric and magnetic field intensities were used to analyze a sample of lead?
c) The problems of maintaining a uniform magnetic field over surfaces larger than 1 square meter are considerable. What separation between lead 207 and lead 208 would be achieved if the diameter of the orbit of lead 208 were held to 1.000 meter?

22.5 Supply the missing data in these transformation equations:

a) ${}_{?}Pb^{212} \rightarrow {}_{?}Bi^{212} + ?;$

b) ${}_{?}Bi^{212} \rightarrow ? + {}_{-1}e^{0};$

c) $? \rightarrow {}_{?}Pb^{208} + {}_{2}He^{4}.$

22.6 The radioactive series originally called the actinium series is now known to start with the uranium isotope ${}_{92}U^{235}$. This parent member undergoes transmutations by emitting in succession the following particles: α, β, α, β, α, α, α, α, β, α, β. This last disintegration yields ${}_{82}Pb^{207}$, which is stable. From this information, and by consulting the periodic table, determine the complete symbol for each member of the series. List the members of the series in a column and beside each member give its mode of decay (similar to what was done in Table 21.1).

22.7 In the following diagram of the thorium series, which begins with ${}_{90}Th^{232}$, the symbols used are those that were originally assigned to the members of the sequence:

$${}_{90}Th^{232} \xrightarrow{\alpha} {}_{?}MsTh_1^{?} \xrightarrow{?} {}_{89}MsTh_2^{?} \xrightarrow{\beta} {}_{?}RaTh^{?} \xrightarrow{\alpha} {}_{?}ThX^{?} \xrightarrow{?}$$

$$Tn^{?} \xrightarrow{?} {}_{84}ThA^{?} \xrightarrow{?} {}_{?}ThB^{?} \xrightarrow{\beta} {}_{?}ThC^{?} \xrightarrow{?} {}_{84}ThC'^{?} \xrightarrow{?}$$

ThD^{208} (stable)

Supply the missing data, then by consulting the periodic table replace the old symbols with the present ones. Indicate where alternative possibilities exist in the series.

22.8 From $_{94}Pu^{241}$, an isotope of plutonium produced artificially by bombarding uranium in a nuclear reactor, a radioactive series has been traced for which the first seven members are $_{94}Pu^{241}$, $_{95}Am^{241}$, $_{93}Np^{237}$, $_{91}Pa^{233}$, $_{92}U^{233}$, $_{90}Th^{229}$ and $_{88}Ra^{225}$. Outline the disintegration series for these first seven members, showing the modes of decay as in the preceding question.

22.9 A trace of radioactivity in natural carbon makes it possible to estimate the age of materials which were once living. The radioactivity of the carbon is due to the presence of a small amount of the unstable isotope, carbon 14. This isotope is created mainly in the upper atmosphere by transformation (induced by cosmic rays) of the stable isotope carbon 13 to carbon 14. The rate of production of carbon 14 from carbon 13 matches the rate of beta-decay of carbon 14 into nitrogen 14, so the percentage of total carbon in the atmosphere consisting of carbon 14 is relatively constant. When carbon dioxide is used by plants in photosynthesis, the resulting cell growth incorporates the isotopes of carbon in the same proportions as exist in the atmosphere. The activity of the carbon at that time is 15.3 beta emissions per minute per gram of carbon. When the interaction with the atmosphere stops, for example, when a branch is broken off a living tree for use as a tool, its radioactivity begins to decrease at a rate characteristic of carbon 14. If the activity is measured at some later time, and if the half-life of carbon 14 is known, then one can use the decay curve given on page 24 to determine the time elapsed since the branch was taken from the tree. For example, suppose the activity dropped from 15.3 to 9.2 beta emissions per minute per gram of carbon. Knowing that the half-life of carbon is 5760 years, determine the time elapsed.

Repeat the procedure to calculate the age of charcoal from an ancient Indian fire pit if the activity of the carbon in the charcoal is found to be 1.0 beta emissions per minute per gram of carbon. What assumption are you making in this part of the problem?

22.10 a) Find the average atomic mass of carbon by calculating the "weighted average" of the atomic masses of the two carbon isotopes. (Use the data of Table 22.1.)

b) Find the average atomic mass of lithium.

c) Find the average atomic mass of lead.

22.11 The mass of a neutral helium is 4.00260 amu, and that of an electron is 0.00055 amu. From these data find the mass of the α particle in amu.

Chapter 23 Probing the Nucleus

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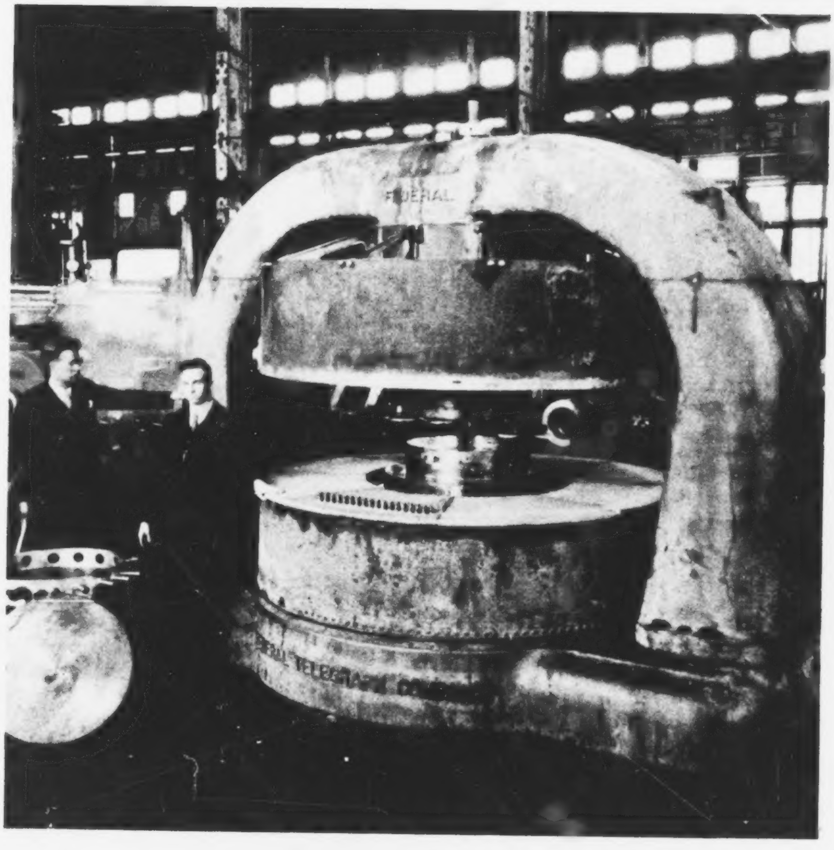


Ernest O. Lawrence (left) and M.S. Livingston (right) are shown standing beside the magnet for one of the earliest cyclotrons. Lawrence and Livingston invented the cyclotron in 1931, thereby initiating the development of high-energy physics in the United States.

23.1 The problem of the composition and structure of the atomic nucleus. The discoveries of radioactivity and isotopes raised new questions about the structure of atoms—questions which involved the atomic nucleus. We saw in Sec. 22.2 that the transformation rules of radioactivity could be described in terms of the Rutherford-Bohr model of the atom. But that model said nothing about the nucleus other than that it has a charge and mass, and that, when radioactive, it emits an α or a β particle. This implies that the nucleus has a composition or structure which changes when a radioactive process occurs. The question arose: how can we develop a theory or model of the atomic nucleus that will explain the facts of radioactivity and the existence of isotopes?

The answer to this question makes up much of what is called nuclear physics. The problem of nuclear structure can be broken into two questions: (1) what are the building blocks of which the nucleus is made, and (2) how are the nuclear building blocks put together? Answers to the first question are considered in this chapter. In the next chapter we shall take up the question of how the nucleus is bound together. The attempt to solve the problem of nuclear structure, although not yet completely successful, has led not only to many new discoveries and to large-scale practical applications, but also to important social and political problems. Indeed, it has had consequences that have stretched far beyond physics and have had a serious impact on society in general. Some of these consequences will be discussed in Chapter 24.

23.2 The proton-electron hypothesis of nuclear structure. The emission of α and β particles by atoms of radioactive nuclides suggested that a model of the nucleus might be constructed by starting with these particles as building blocks. Such a model might be expected to be useful for the radioactive elements, because it would make it easy to see, for example, how a number of α particles could be emitted, in succession, in a radioactive series. But not all nuclei have masses that are multiples of the α-particle mass. Moreover, the nucleus of an atom of the lightest element, hydrogen, with an atomic mass of one unit (two units in the case of the heavy isotope), is too light to contain an α particle. So is the light isotope of helium, ${}_2He^3$.

SG 23.1

A positively charged particle with a mass of one unit would be more satisfactory as a nuclear building block. Such a particle does indeed exist: the nucleus of the common isotope of hydrogen. This particle has been named the proton. According to the Rutherford-Bohr theory of atomic structure, the hydrogen atom consists of a proton with a single electron revolving around it.

Proton—from the Greek "protos" (first). It is not known who suggested the name originally—it is found in the literature as far back as 1908. In 1920 Rutherford's formal proposal of the name proton was accepted by the British Association for the Advancement of Science.

In the preceding chapter (Sec. 22.4), we discussed Aston's whole-number rule, expressing the experimental result that the atomic masses of the nuclides are very close to integers. This rule, together with the properties of the proton—its mass of very nearly one unit and its single positive charge—made it appear possible that all atomic nuclei are made up of protons. Could a nucleus of mass number A consist of A protons? If this were the case, the charge of the nucleus would be A units; but, except for hydrogen, the nuclear charge Z is always less than A—usually less than ½A. To get around this difficulty, it was assumed that in addition to the protons, atomic nuclei contain just enough electrons to cancel the charge of the extra protons, that is, A-Z electrons. These electrons would contribute only a small amount to the mass of the nucleus, but would make the net charge equal to +Z units as required. It was thus possible to consider the atom as consisting of a nucleus of A protons and A-Z electrons, with Z additional electrons outside the nucleus to make the entire atom electrically neutral. For example, an atom of $_8O^{16}$ would have a nucleus with 16 protons and 8 electrons, with 8 additional electrons outside the nucleus. This model of the nucleus is known as the proton-electron hypothesis of nuclear composition. SG 23.2

The proton-electron hypothesis seemed to be consistent with the emission of α and β particles by atoms of radioactive substances. Since it was assumed that the nucleus contained electrons, explanation of beta decay was no problem: when the nucleus is in an appropriate state it may simply eject one of its electrons. It also seemed reasonable that an α particle could be formed, in the nucleus, by the combination of four protons and two electrons; an α particle might exist as such, or it might be formed at the instant of emission.

The proton-electron hypothesis is similar to an earlier idea suggested by English physician William Prout in 1815. On the basis of the small number of atomic masses then known, he proposed that all atomic masses are whole numbers, that they might be integral multiples of the atomic mass of hydrogen and that all the elements might be built up of hydrogen. Prout's hypothesis was discarded when, later in the nineteenth century, the atomic masses of some elements were found to be fractional, in particular, those of chlorine (35.46 units) and copper (63.54 units). With the discovery of isotopes, it was found that the fractional atomic masses of chlorine and copper, like that of neon, are those of mixtures of isotopes, but each separate isotope has an atomic mass very close to an integer.

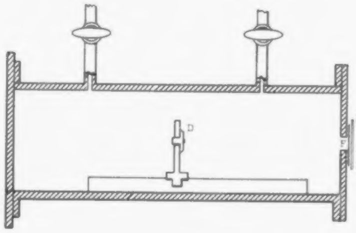
Although the proton-electron hypothesis was satisfactory in some respects—as in accounting for nearly integral (whole number) isotopic masses and in being consistent with the emission of α and β particles by radioactive nuclides—it led to serious difficulties and had to be given up. The existence of electrons inside the nucleus had to be ruled out for a number of reasons too complicated to discuss at this point.

Q1 Why was the idea of hydrogen atoms being a basic building block of all atoms given up in the nineteenth century?

Q2 On the basis of the proton-electron hypothesis, what would a nucleus of $_6C^{12}$ contain?

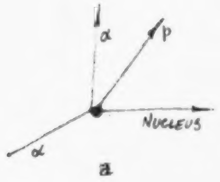
23.3 The discovery of artificial transmutation.

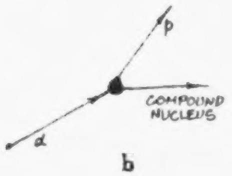
A path which led to a better understanding of nuclear composition was opened in 1919. In that year Rutherford found that when nitrogen gas was bombarded with α particles from bismuth 214, swift particles were produced which could travel farther in the gas than did the α particles themselves. When these particles struck a scintillation screen, they produced flashes of light of the same intensity as would be produced by positive hydrogen ions (protons). Measurements of the effect of a magnetic field on the paths of the particles suggested that they were indeed protons. Rutherford ruled out, by means of careful experiments, the possibility that the protons came from hydrogen present as an impurity in the nitrogen. Since the nitrogen atoms in the gas were the only possible source of protons, Rutherford concluded that an α particle, in colliding with a nitrogen nucleus, can occasionally knock a small particle—a proton—out of the nitrogen nucleus. In other words, Rutherford deduced that an α particle can cause the artificial disintegration of a nitrogen nucleus, with one of the products of the disintegration being a proton. The experimental results showed that only one proton was produced for about one million α particles passing through the gas. Between 1921 and 1924, Rutherford and Chadwick extended the work on nitrogen to other elements and found evidence for the artificial disintegration of all the light elements from boron to potassium, with the exception of carbon and oxygen.



Rutherford's diagram of the apparatus used to detect the protons from disintegrations produced by α particles. The α source was on a movable stand. Nitrogen nuclei in the nitrogen gas which filled the box are transmuted by the α's. At the end of the box was a piece of silver foil thick enough to stop α's, but not protons. Behind the foil was a lead sulfide screen which would show flashes of light when struck by protons. (The photo on p. 73 of the Unit 5 Text shows Rutherford holding this apparatus.)

The next step was to determine the nature of the nuclear process leading to the emission of the proton. Two hypotheses were suggested for this process: (a) the nucleus of the bombarded atom promptly loses a proton "chipped off" as the result of a collision with a swift α particle; or (b) the α particle is captured by the nucleus of the atom it hits forming a new nucleus which, a moment later, emits a proton. It was possible to distinguish experimentally between these two possible cases by using a device, called a "cloud chamber," which reveals the path or track of an individual charged particle. The cloud chamber was invented in 1912 by C. T. R. Wilson; a schematic diagram of the instrument is shown in Fig. 23.1. In case (a) four tracks should be seen in a photograph of a disintegration event: the track of the α particle before the collision, the track of the α particle after collision and the tracks of the proton and recoiling nucleus after collision. In case (b) the α particle should disappear in the collision, and only three tracks would be seen: that of the α particle before the collision and the tracks of the proton and recoil nucleus after the collision. The choice between the two possibilities was settled in 1925 when P. M. S. Blackett studied the tracks produced when α particles passed through nitrogen gas in a cloud chamber. He found, as shown in Fig. 23.2, that the only tracks which could be seen were those of the incident α particle, a proton and the recoil nucleus. The absence of a track corresponding to the presence of an α particle after the collision proved that the α particle disappeared completely and that case (b) is the correct interpretation.





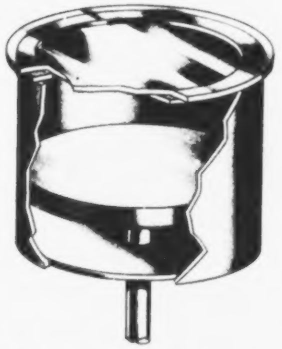


Fig. 23.1 The Wilson cloud chamber. When the piston is moved down rapidly the gas in the cylinder becomes supersaturated with water vapor. The water vapor will condense on the ions created along the path of a high-energy charged particle, thereby making the track.

For his invention of the cloud chamber Charles Thomson Rees Wilson (1869-1959) of Scotland shared the 1927 Nobel Prize in physics with Arthur H. Compton.

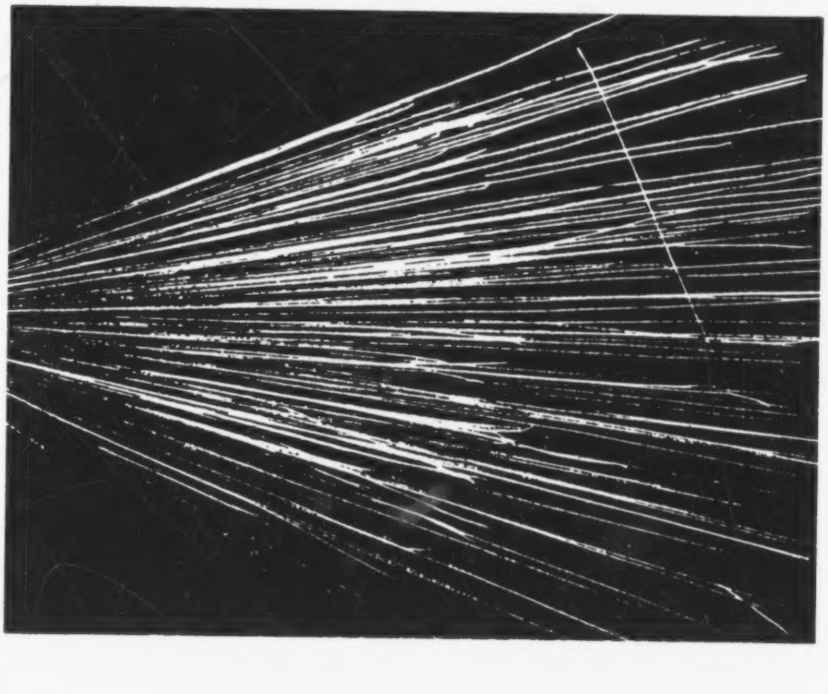
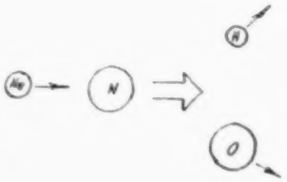


Fig. 23.2 α-particle tracks in a cloud chamber filled with nitrogen gas. At the right, one α particle has hit a nitrogen nucleus; a proton is ejected upward toward the left, and the resulting oxygen nucleus recoils downward to the right. (From P. M. S. Blackett, 1925)

The process in which an α particle is absorbed by a nitrogen nucleus and a proton is emitted may be represented by an equation which is analogous to the equations used near the end of Sec. 22.6 to represent radioactive decay. The equation expresses the fact that the total mass number is the same before and after the collision (conservation of mass number) and the fact that the total charge is the same before and after the collision (conservation of charge). The atomic number, the mass number and the nuclear charge are known for the target nucleus $_7N^{14}$, the incident α particle $_2He^4$ and the proton $_1H^1$. The product nucleus will therefore have the atomic number 7 + 2 - 1 = 8, and the mass number 14 + 4 - 1 = 17. The product nucleus is $_8O^{17}$, an isotope of oxygen, and the disintegration process may be represented by the nuclear reaction:

See "The Tracks of Nuclear Particles" in Project Physics Reader 6.

$$_2He^4 + {_7N^{14}} \longrightarrow {_8O^{17}} + {_1H^1}.$$



This reaction shows that a transmutation of an atom of one chemical element into an atom of another chemical element has taken place. This transmutation did not occur spontaneously, as is the case in natural radioactivity, but was man-made; it was produced by bombarding target atoms (nuclei) with projectiles from a radioactive nuclide. In the paper in which he reported this first artificially produced nuclear reaction, Rutherford said,

SG 23.3

> The results as a whole suggest that, if α particles—or similar projectiles—of still greater energy were available for experiment, we might expect to break down the nuclear structure of many of the lighter atoms.

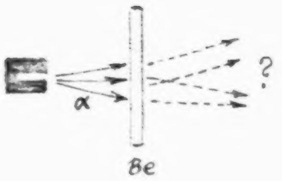
The further study of reactions involving light nuclei led (as we shall see in the next section) to the discovery of a new particle—the neutron—and to a better theory of the constitution of the nucleus. Many types of reactions have been observed with nuclei of all masses, from the lightest to the heaviest, and the possibilities indicated by Rutherford have been realized to an extent far beyond what he could have imagined in 1919.

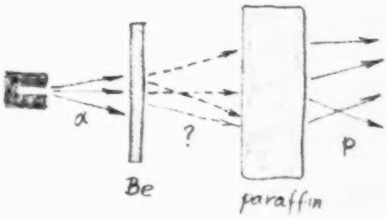
Q3 What evidence showed that the bombarding α particle was absorbed by the nitrogen nucleus, rather than bounced off?

23.4 The discovery of the neutron.

It was suggested by Rutherford in 1920 that an electron and a proton inside the nucleus might be tied to each other so closely as to form a neutral particle. Rutherford even suggested the name "neutron" for this particle. Physicists looked for neutrons, but the search presented at least two difficulties: (1) there were no naturally occurring sources of neutrons; and (2) the methods used for detecting atomic particles all depended on effects of the electric charge of the particles and could not be applied directly to neutral particles. Until 1932, the search for neutrons was unsuccessful.

The proof of the existence of neutrons by the English physicist, James Chadwick, came in 1932 as the result of a series of experiments on nuclear reactions made by physicists in different countries. The discovery of the neutron is a good example of how physicists operate—how they think about problems and arrive at solutions; it is an excellent "case history" in experimental science. Working in Germany in 1930, W. G. Bothe and H. Becker found that when samples of boron and beryllium were bombarded with α particles, they emitted radiations which appeared to be of the γ-ray type, that is, which had no electric charge. Beryllium gave a particularly marked effect of this kind. Observations by physicists in Germany, France and Great Britain showed that the radiation from the beryllium penetrated further (in lead, for example) than any γ radiation found up to that time and had an energy of about 10 MeV. The radiation was thus much more energetic than the γ rays previously observed, and, as a result, aroused much interest. Among those who investigated this radiation were the French physicists Frédéric Joliot and his wife Irène Curie, a daughter of the discoverers of radium; they studied the absorption of the radiation in paraffin, a material rich in hydrogen. They found in the course of their experiments that the radiation from beryllium, when it fell on paraffin, ejected large numbers of protons from the paraffin. The energies of these protons were found to be about 5 MeV. Using the principles of conservation of momentum and energy, they calculated the energy a γ ray would need if it were to transfer 5 MeV to a proton in a collision. The result was about 50 MeV, a value much greater than the 10 MeV that had been measured. In addition, the number of protons produced was found to be much greater than that predicted on the assumption that the radiation consisted of γ rays, that is, photons or quanta of radiation.





James Chadwick (born 1891) received the Nobel Prize in Physics in 1935 for his discovery of the neutron.

These discrepancies (between the results of two sets of experiments and between theory and experiment) left physicists in a dilemma. Either they could give up the application of conservation of momentum and energy to the collisions between the radiation and the protons in the paraffin, or they could adopt another hypothesis about the nature of the radiation. Now, if there is any one thing physicists do not want to do it is to give up the principles of conservation of momentum and energy. These principles are so basic to scientific thought and have proven so useful that physicists tried very hard to find an alternative to giving them up.

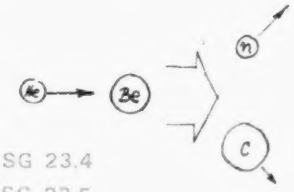
See "Conservation Laws" in Project Physics Reader 6.

In 1932, Chadwick found a successful alternative, a new hypothesis about the nature of the radiation. In his paper "The Existence of a Neutron," he said:

> If we suppose that the radiation is not a quantum radiation, but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfers to different masses. In order to explain the great penetrating power of the radiation, we must further assume that the particle has no net charge. We must suppose it to consist of a proton and electron in close combination, the 'neutron' discussed by Rutherford in his Bakerian Lecture of 1920.

According to Chadwick's hypothesis, when a light element (such as beryllium) is bombarded with α particles, a second kind of nuclear reaction can take place (in addition to the one that produces protons):

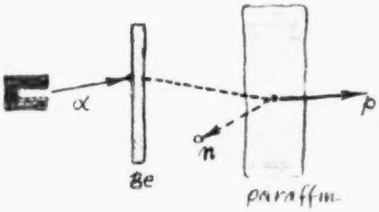
$$_2He^4 + {}_4Be^9 \longrightarrow {}_6C^{12} + {}_0n^1.$$



The symbol $_0n^1$ represents the neutron postulated by Chadwick, with zero charge and mass number equal to 1.

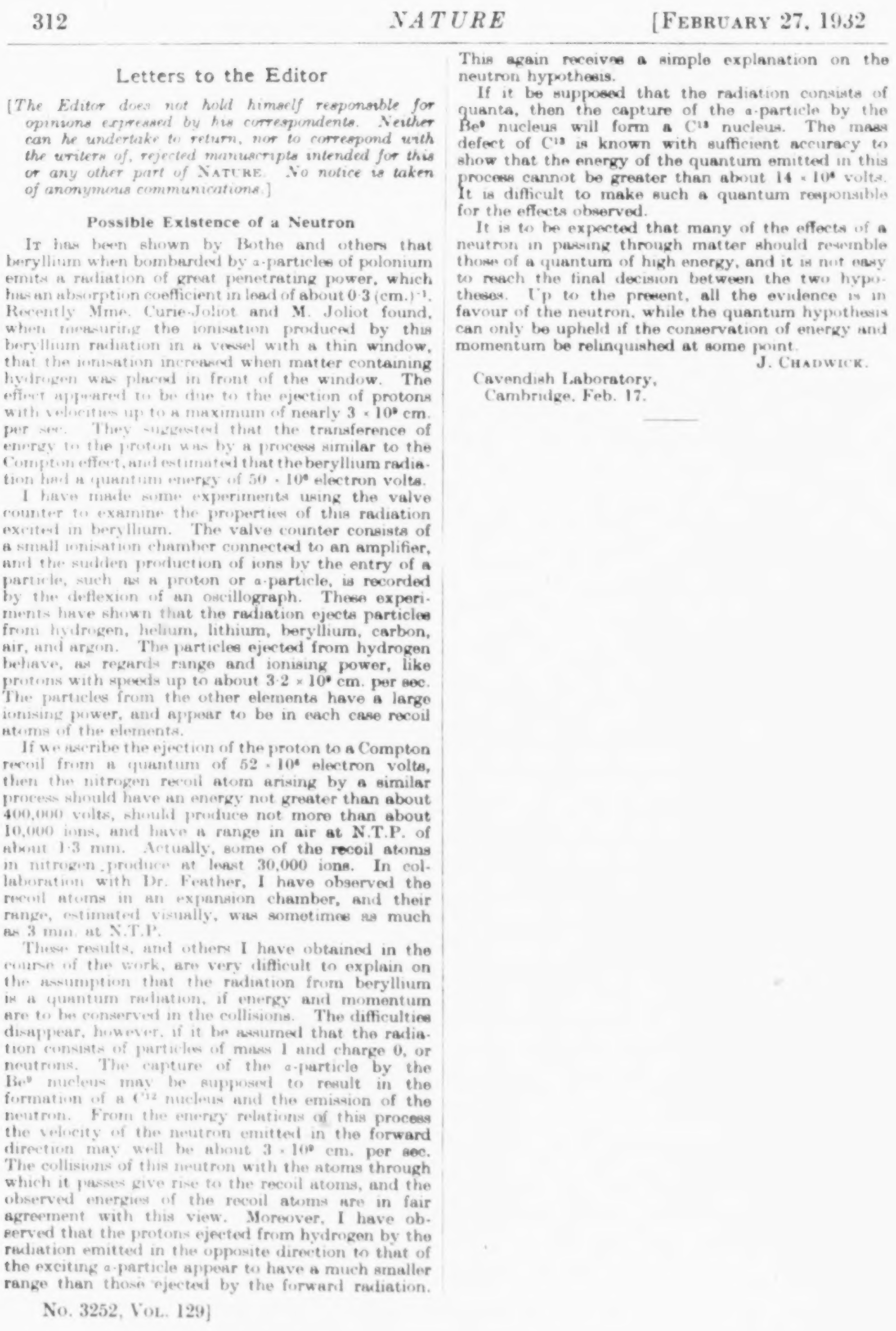
SG 23.4
SG 23.5

The neutrons postulated by Chadwick had no charge, and could even penetrate bricks of a material as dense as lead without giving up their energy. Neutrons could also approach charged nuclei without being repelled or deflected by strong electrostatic forces, as α particles are deflected when scattered by nuclei. In a head-on collision with a hydrogen nucleus (proton), whose mass should be very close to that of the neutron, the neutron could give up practically all its kinetic energy to the proton. The latter could then be observed because of the ionization it produces, and its kinetic energy could be determined. Thus Chadwick's hypothesis could account in a qualitative way for the observed effects of the "radiation" from beryllium.



It was still necessary, however, to determine the mass of the neutron quantitatively, and this Chadwick did by means of some additional experiments. His method was based on the fact that in a collision between a moving and a stationary particle, the speed imparted to the latter is greatest in a head-on collision, in which the stationary particle now moves off in the same direction as that in which the incident particle approached it. A formula for the maximum speed can be derived from the equations of conservation of energy and momentum in a head-on collision.

See "Some Personal Notes on the Search for the Neutron" in Project Physics Reader 6.



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Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3·2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

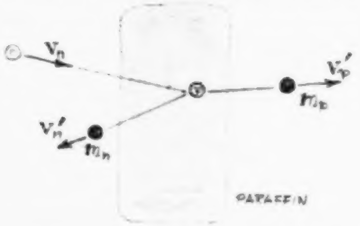
J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

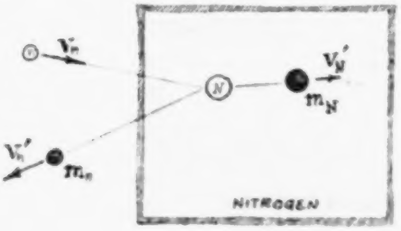
No. 3252, VOL. 129]

Chadwick's first published report of his neutron conjecture.

Determining the Neutron's Mass



The sketch above represents the perfectly elastic collision of a neutron and a proton. To determine the mass of the neutron, we proceed by considering a head-on collision: conservation of kinetic energy and conservation of momentum provide two algebraic equations which must both hold. Combining the equations algebraically (solving the momentum equation for v_n', substituting this for v_n' in the energy equation, expanding, collecting terms and solving for v_p') leads to an expression for v_p'. This expression includes the term v_n, however, which can't be measured. We can eliminate v_n from the equation by analyzing another collision and combining the results with what we already have.



The sketch above represents a perfectly elastic collision between a neutron and a nitrogen nucleus. When the collision is head-on, we can write energy and momentum equations similar to what we wrote before, but this time leading to an expression for v_N'. This expression also includes the unmeasurable v_n.

The v_p' equation and v_N' equation are then combined algebraically (eliminating the v_n) and solved for m_n. The expression for m_n now contains only terms which can be measured—so m_n can be calculated.

CONSERVATION OF ENERGY

$$\frac{1}{2}m_n v_n^2 = \frac{1}{2}m_n v_n'^2 + \frac{1}{2}m_p v_p'^2$$

CONSERVATION OF MOMENTUM

$$m_n v_n = m_n v_n' + m_p v_p'$$

$$\downarrow$$

$$v_n' = \frac{m_n v_n - m_p v_p'}{m_n}$$

$$\frac{1}{2}m_n v_n^2 = \frac{1}{2}m_n\left(\frac{m_n v_n - m_p v_p'}{m_n}\right)^2 + \frac{1}{2}m_p v_p'^2$$

$$m_n v_n^2 = \frac{m_n^2 v_n^2 - 2m_n m_p v_n v_p' + m_p^2 v_p'^2}{m_n} + m_p v_p'^2$$

$$m_n^2 v_n^2 = m_n^2 v_n^2 - 2m_n m_p v_n v_p' + m_p^2 v_p'^2 + m_n m_p v_p'^2$$

$$m_p^2 v_p'^2 + m_n m_p v_p'^2 = 2m_n m_p v_n v_p'$$

$$m_p v_p' + m_n v_p' = 2m_n v_n$$

$$v_p' = \frac{2m_n v_n}{m_p + m_n}$$

CONSERVATION OF ENERGY

$$\frac{1}{2}m_n v_n^2 = \frac{1}{2}m_n v_n'^2 + \frac{1}{2}m_N v_N'^2$$

CONSERVATION OF MOMENTUM

$$m_n v_n = m_n v_n' + m_N v_N'$$

$$v_N' = \frac{2m_n v_n}{m_N + m_n}$$

$$\frac{v_p'}{v_N'} = \frac{m_N + m_n}{m_p + m_n}$$

$$\downarrow$$

$$m_n = \frac{m_N v_N - m_p v_p}{v_p - v_N}$$

Chadwick calculated the mass of the neutron to be 1.16 amu. The difficulties of measuring the speeds of recoil H^1 and N^{14} kept this from being a very precise value, but it was good enough to show that the neutron has a mass close to that of the proton; thus Chadwick's hypothesis did indeed offer a satisfactory solution to the problem of the "radiation" emitted when boron and beryllium were bombarded with α particles. In more precise experiments, Chadwick found that the neutron mass is between 1.005 and 1.008 amu. The best methods now available for determining the neutron mass give 1.008665 amu as compared with the proton mass of 1.007276 amu (based on the scale $C^{12} = 12.000\,000$).

SG 23.5
SG 23.6

Much research has been done since 1932 on the properties of neutrons and on the interactions between neutrons and atoms. A branch of study called neutron physics has been developed. Neutron physics deals with the production of neutrons, their detection and their interaction with atomic nuclei and with matter in bulk. This research has led, among other things, to the discovery of nuclear fission, to be discussed in Chapter 24.

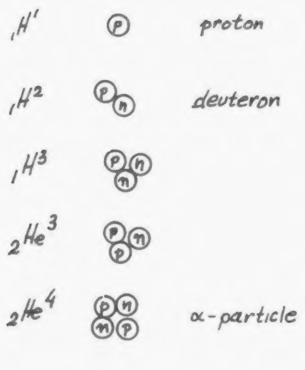
Q4 Why wasn't the penetrating radiation from bombarded beryllium interpreted as being γ rays?

Q5 Why did the mass of a neutron have to be investigated by measurements on protons?

23.5 The proton-neutron theory of the composition of atomic nuclei.

The discovery of the neutron, with an atomic mass close to one unit and with no electric charge, confirmed Rutherford's suggestion that the atomic nucleus is made up of protons and neutrons. This hypothesis was soon used as the basis of a detailed theory of the nucleus by Heisenberg in 1932, and is still the basis of attempts to describe the properties and structure of the nucleus. According to the proton-neutron hypothesis, the nucleus of atomic number Z and mass number A consists of Z protons and A-Z neutrons. The nuclei of the isotopes of a given element differ only in the number of neutrons they contain. Thus the nucleus of the hydrogen isotope of mass number 1 contains one proton; the nucleus of deuterium (hydrogen isotope of mass number 2) contains one proton and one neutron. The nucleus of the neon isotope Ne^{20} contains 10 protons and 10 neutrons; while that of Ne^{22} contains 10 protons and 12 neutrons. The atomic number Z, identified with the change in the nucleus, is the number of protons it contains. The mass number A is the total number of protons and neutrons. If we use the term nucleons to refer to both kinds of nuclear particles, then A is the number of nucleons.

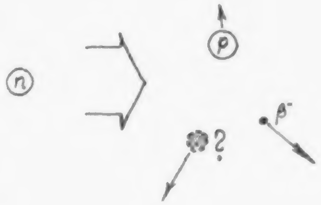
SG 23.8
SG 23.9



See "Models of the Nucleus" in Project Physics Reader 6.

The proton-neutron hypothesis can be shown to be consistent with the facts of radioactivity. If two protons and two neutrons could combine, the resulting particle would have Z=2 and A=4—just the properties of the α particle. The emission of the combination of two protons and two neutrons (in the form of an α particle) would be consistent with the first transformation rule of radioactivity. (The α particle might exist as such in the nucleus, or it might be formed at the instant of emission; the latter possibility is now considered more likely.) But, if the nucleus consists of protons and neutrons, where could a β particle come from? This question is more difficult to answer than that of the origin of an α particle. The second transformation rule of radioactivity provides a clue: when a nucleus emits a β particle its charge Z increases by one unit while its mass number A remains unchanged. This would happen if a neutron were to change into a proton and a β particle.

We now know that a free neutron—a neutron separated from an atom—changes into a proton, an electron and another, uncharged particle (which we shall discuss later). The disintegration of the neutron is a transformation into three particles, not just the separation of a neutron into a proton and an electron. The half-life of free neutrons is about 12 minutes. In the β decay of a radioactive nucleus (since β particles are not present in the nucleus) a β particle must be created in the act of β decay. This can occur if a neutron in the nucleus is transformed into a proton, an electron (and the not-yet discussed neutral particle). This concept forms the basis of the currently accepted theory of β decay, a theory which has successfully accounted for all the known phenomena of β decay.



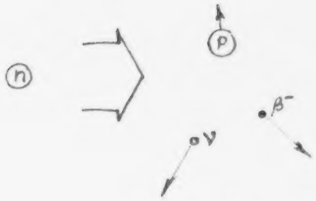
Q6 According to the proton-neutron theory of the nucleus, what is in the nucleus of $_7N^{14}$?

Q7 Describe a helium atom in terms of the three elementary particles: proton, neutron and electron.

Q8 If nuclei do not contain β particles, how can β emission be explained?

23.6 The neutrino.

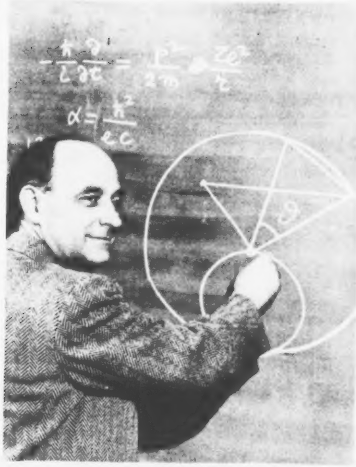
The description of β decay in terms of the transformation of a neutron in the nucleus involves one of the most fascinating stories in modern physics: the prediction and eventual discovery of the particles known as the neutrino and the antineutrino. Quantitative studies of the energy relations in β decay during the 1920's and 1930's raised a difficult and serious question. Methods were devised for determining the energy change in a nucleus



during β decay. According to the principle of conservation of energy, the energy lost by the nucleus should be equal to the energy carried off by the β particle. But, when the energy lost by the nucleus was compared with the measured kinetic energy of the β particle, the latter was nearly always smaller: some of the energy lost by the nucleus seemed to have disappeared. Measurements made on a large number of β - emitters indicated that about two-thirds of the energy lost by the β-decaying nuclei seemed to disappear. Attempts to find the missing energy failed. For example, some physicists thought that the missing energy might be carried off by γ rays; but no such γ rays could be detected experimentally. The principle of conservation of energy seemed to be violated in β decay. Similar discrepancies were found in measurements of the momentum of the electron and the recoiling nucleus.

As in the case of the experiments that led to the discovery of the neutron, physicists tried very hard to find an alternative to accepting the failure of the principles of conservation of energy and momentum. An Austrian physicist, Wolfgang Pauli, Jr., suggested in 1933 that another particle is emitted in β decay along with the electron, and that this particle carries off the missing energy and momentum. This hypothetical particle would have no electric charge because the positive charge of the proton and the negative charge of the electron together are equal to the zero charge of the neutron. (Conservation of electric charge!) The mass-energy balance in the decay of the neutron indicated that the mass of the hypothetical particle should be very small—much smaller than the mass of an electron, and possibly even zero. The combination of zero electric charge and zero or nearly zero mass would make the particle extremely hard to find.

The Italian physicist Enrico Fermi called the suggested particle the "neutrino" or "little neutron." In 1934 Fermi constructed a theory of β decay based on Pauli's suggestion. This theory has been successful, as mentioned earlier, in describing all the known facts of β decay. From 1934 on, the neutrino was accepted as a "real" particle for two reasons, both theoretical: it saved the principle of conservation of energy in β decay, and it could be used successfully both to describe the results of experiments in β decay and to predict the results of new experiments. Many unsuccessful attempts were made to detect neutrinos over a period of 25 years. Finally, in 1959, neutrinos were detected in an experiment using the extremely large flow of neutrinos that comes out of a nuclear reactor (see Chapter 24). The detection of neutrinos involves detecting the products of a reaction



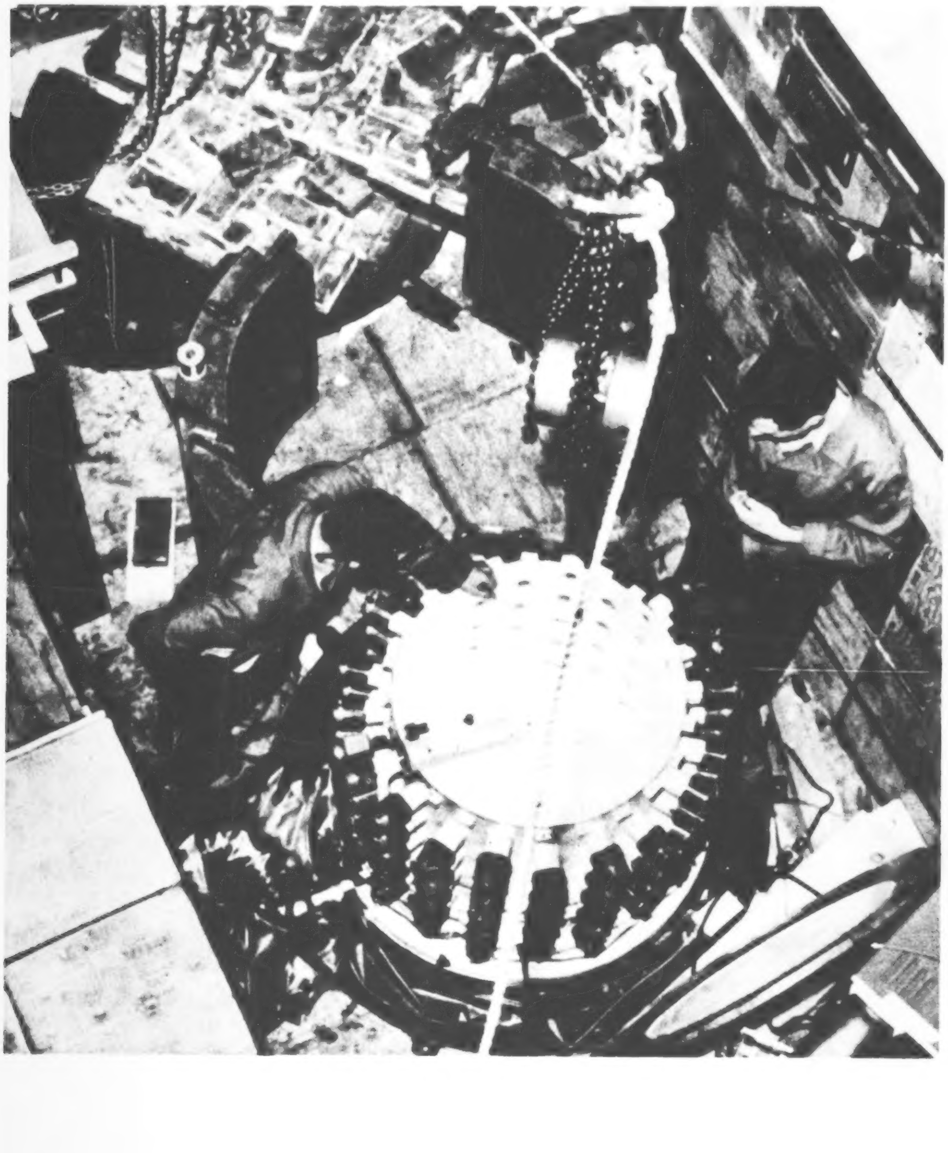
Enrico Fermi, one of the most productive physicists of this century.

provoked by a neutrino. The reaction used was reverse β decay—the production of a proton from a neutron. Again the faith of physicists in the principle of conservation of energy was justified.

There is still one more complication: it is now known that there are several kinds of neutrinos. The one involved in β decay (as discussed so far) is referred to as an antineutrino, and is denoted by the symbol $\bar{\nu}$ (Greek letter "nu," with a bar over it). The transformation of a neutron is then written:

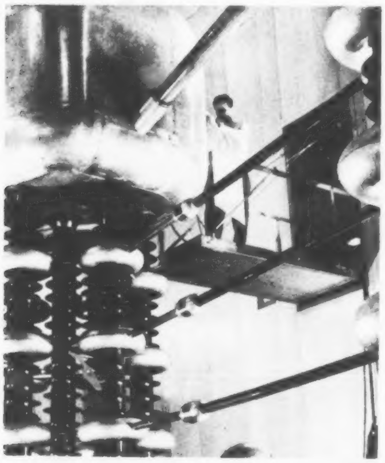
$$_{1}n^{0} \longrightarrow {}_{1}p^{1} + {}_{-1}e^{0} + \bar{\nu}$$

Q9 Why was an unknown, almost undetectable particle invented to patch up the theory of β decay?

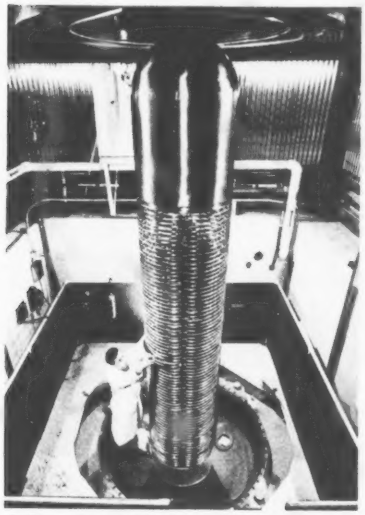


The first detection of neutrinos was in this tank. Reactions provoked by neutrinos cause flashes of light in the liquid with which the tank is filled. The flashes are detected by the photoelectric tubes which stud the tank wall.

See "The Evolution of the Cyclotron" and "The Cyclotron as Seen by..." in Project Physics Reader 6.



First stage of a 750 kilovolt proton accelerator (see p. 59 of Unit 4).



A Van de Graaff generator built on a vertical axis.

23.7 The need for particle accelerators.

Up to 1932 the study of nuclear reactions was limited by the kind of projectile that could be used to bombard nuclei: only α particles from the naturally radioactive nuclides could bring about reactions. Progress was limited because α particles could be obtained only in beams of low intensity and with energies less than 8 MeV. These relatively low-energy particles could produce transmutations only in light elements. When heavier elements are bombarded with α particles, the repulsive electric force exerted by the greater charge of the heavy nucleus on an α particle makes it difficult for the α particle to reach the nucleus. The probability of a nuclear reaction taking place becomes very small—almost zero. But because the interest in nuclear reactions was great, physicists sought methods of increasing the energy of charged particles to be used as projectiles.

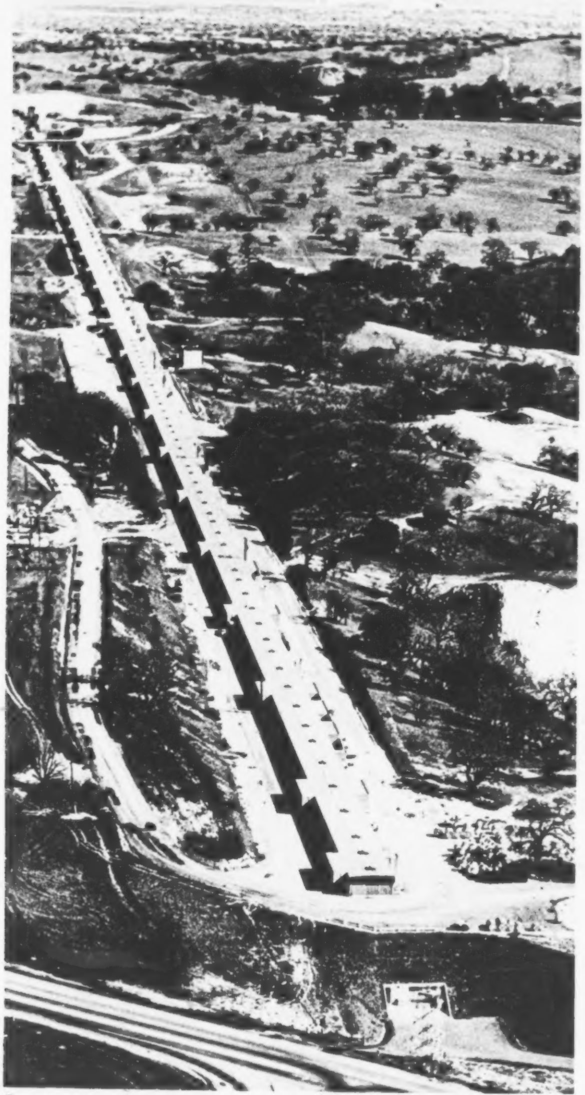
There were advantages to be gained by using particles that have only one positive charge—particles such as the proton or the deuteron (the nucleus of the deuterium atom). Having but a single charge, these particles would experience smaller repulsive electric forces than would α particles in the neighborhood of a nucleus, and thus might succeed in producing transmutations of heavy target nuclei. Protons or deuterons could be obtained from positive-ray tubes, but their energies would not be high enough. Some device was needed to accelerate these charged particles to higher energies. Such devices might also offer other advantages: the speed (and energy) of the bombarding particles could be controlled by the experimenter; and very intense projectile beams might be obtained. It would be possible to find how the variety and abundance of nuclear reactions depend on the energy of the bombarding particles.

Since 1930 many devices for accelerating charged particles have been invented. In each case the particles (electrons, protons, deuterons, α particles or heavy ions) are accelerated by an electric field. In some cases a magnetic field is used to control the path of the particles, that is, to steer them. Accelerators have become basic tools for research in nuclear and high-energy physics. Also, they are used in the production of radioactive isotopes and serve as radiation sources for medical and industrial purposes. The table presented on the next page summarizes the major types of particle accelerators now being used.

Next on the long-range planning list of the U.S. Atomic Energy Commission is a 200 BeV particle accelerator to be

Table 23.1 Major types of particle accelerators

Type	Principle of Operation	Maximum Energy	Particles	Notes
ONCE-THROUGH ACCELERATION				
Cockcroft-Walton	direct high voltage potential	≈4 MeV	various	commercially available
Van de Graaff generator	high voltage by moving belt	≈3 MeV ≈14 MeV	electrons protons	commercially available
Linear accelerator	successive application of high frequency voltages	≈10 MeV per particle	heavy ions	Lawrence Radiation Laboratory and Yale University
Linear accelerator	pulsed high frequency wave	≈20 BeV	electrons	Stanford University, two miles long
CYCLIC ACCELERATION				
Betatron	magnetic induction (electrons accelerated in an evacuated tube between the poles of an electromagnet)	≈300 MeV	electrons	Largest machine at the University of Illinois
Cyclotron	voltage of constant frequency applied to particles in fixed magnetic field	≈12 MeV ≈24 MeV ≈48 MeV	protons deuterons particles	numerous installations
Synchro-cyclotron	voltage of variable frequency applied to particles in fixed magnetic field	≈750 MeV	protons	184-inch unit at Lawrence Radiation Laboratory, Berkeley
Electron synchrotron	voltage of constant frequency applied to particles orbiting in variable magnetic field	≈7 BeV	electrons	Hamburg, Germany (7.5 BeV), Cambridge Electron Accelerator (6 BeV) operated by Harvard and M.I.T.
Proton synchrotron	synchronized voltage of high frequency applied to particles orbiting in variable magnetic field	≈12 BeV	protons	6.2 BeV "Bevatron" at Lawrence Radiation Laboratory, 3 BeV Cosmotron at Brookhaven, 3 BeV at Princeton, and 12.5 BeV synchrotron at Argonne National Laboratory
Alternating gradient synchrotron	same as synchrotron except successive segments of magnetic field have opposite curvature.	≈30 BeV	protons	Brookhaven National Laboratory (Long Island) and CERN, Switzerland
		≈70 BeV	protons	Serpukhov, U.S.S.R.
Strong-focusing synchrotron	"	≈200-400 BeV protons		Weston, Illinois (in planning and design stage)



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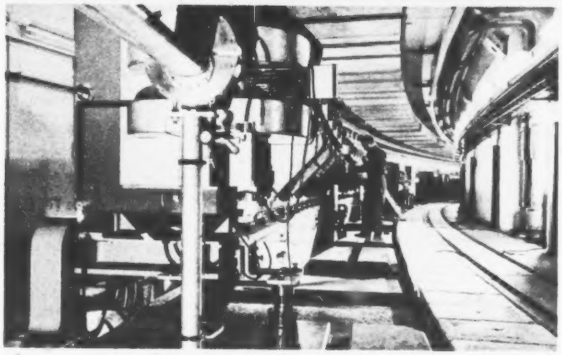

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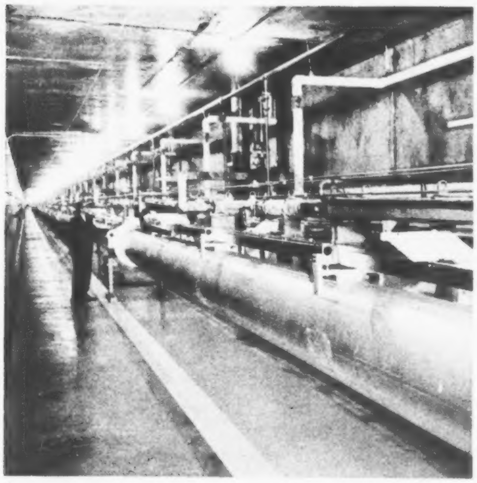

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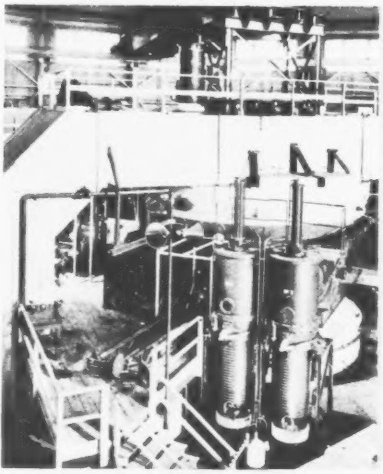
a. b. The Stanford "Linac" (linear accelerator).

c. d. The CERN proton synchotron at Geneva. The evacuated ring in which the protons are accelerated is at the upper left of d.

e. The 184" cyclotron at Berkeley.

f. The Brookhaven Cosmotron, in operation from 1952 to 1967, has been superceded by larger accelerators.



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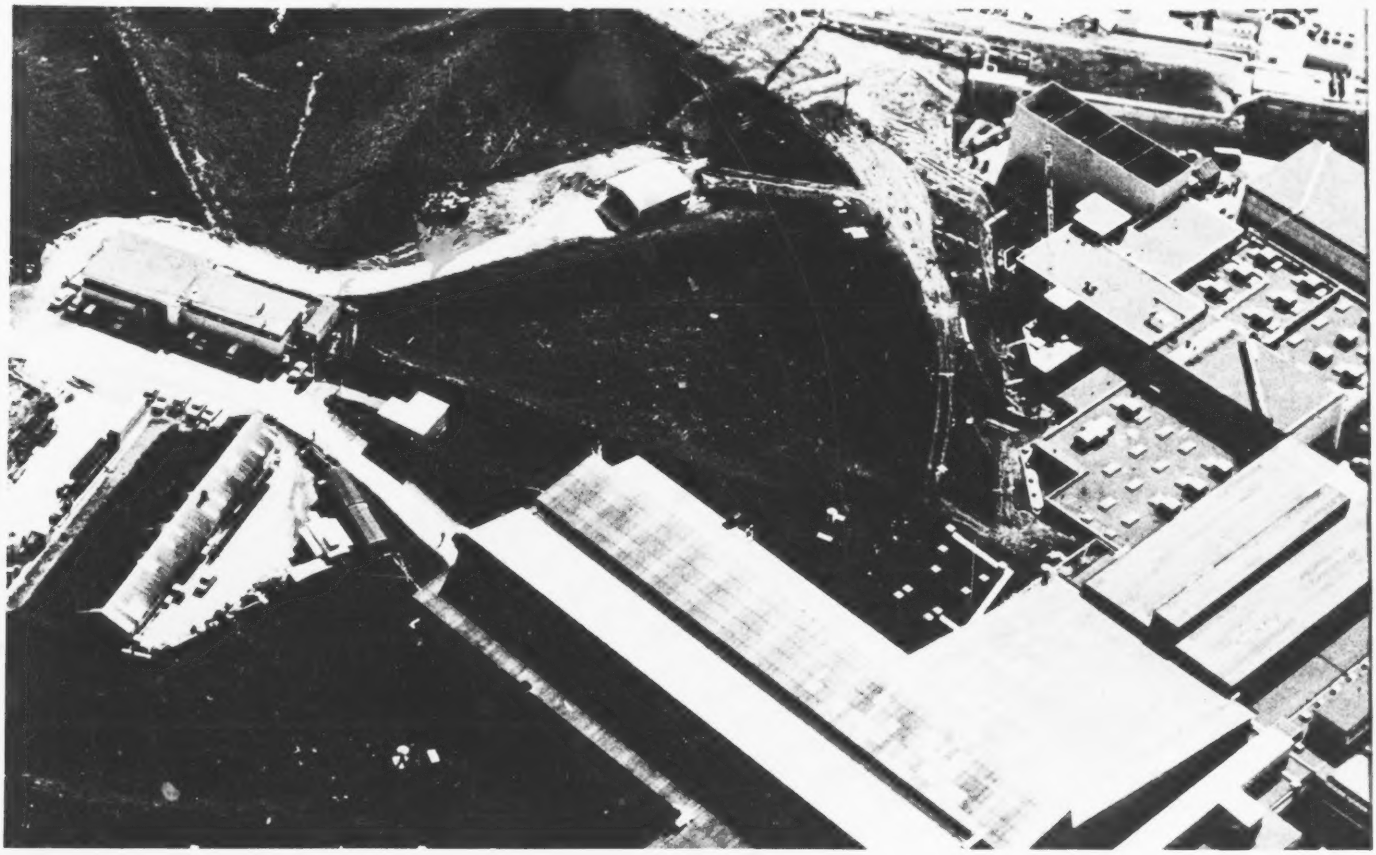

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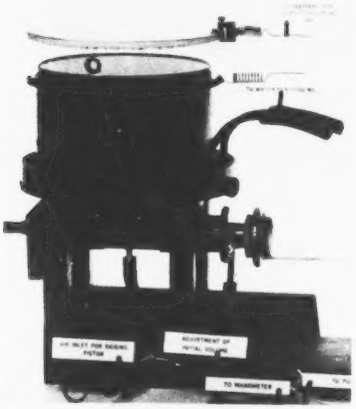
completed by 1973 for approximately $240 million. Initial plans for an 800 to 1000 BeV machine are being formulated; construction should begin by 1971 at a cost of about $800 million. Why is a nation willing to budget such sums for larger and larger particle accelerators? What do we plan to discover with these high-energy machines? Basically, the answer is a simple one: we would like to find out as much as we can about the structure of nuclear particles and the nature of the forces holding them together.

With the discovery of the neutron in 1932 it was believed that three "elementary" particles act as the building blocks of matter: the proton, the neutron and the electron. We have mentioned the existence of new particles, such as neutrinos and antineutrinos. As high-energy accelerators became available, additional "elementary" particles were discovered one after another. In the appendix is a list of some of these

a. Wilson's cloud chamber.
b. Particle tracks in a cloud chamber.
c. The tiny bubble chamber, 3 cm long, invented by D.A. Glaser in 1952. Glaser was 26 at the time and 8 years later was awarded the Nobel Prize for his invention. (Note the particle track.)
d. The 200 cm Bubble Chamber Assembly at the Brookhaven National Laboratory.



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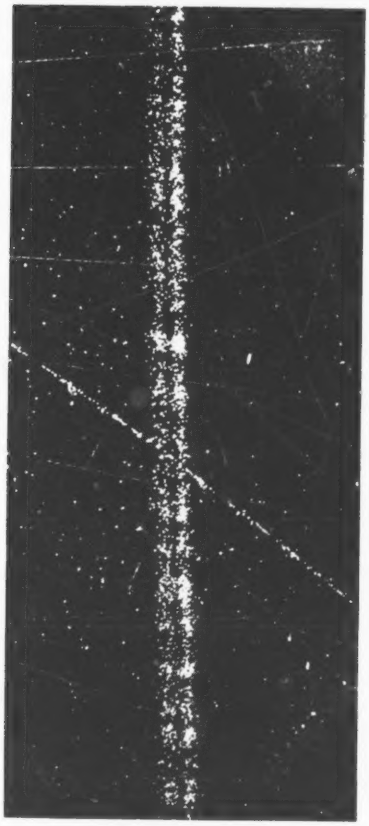

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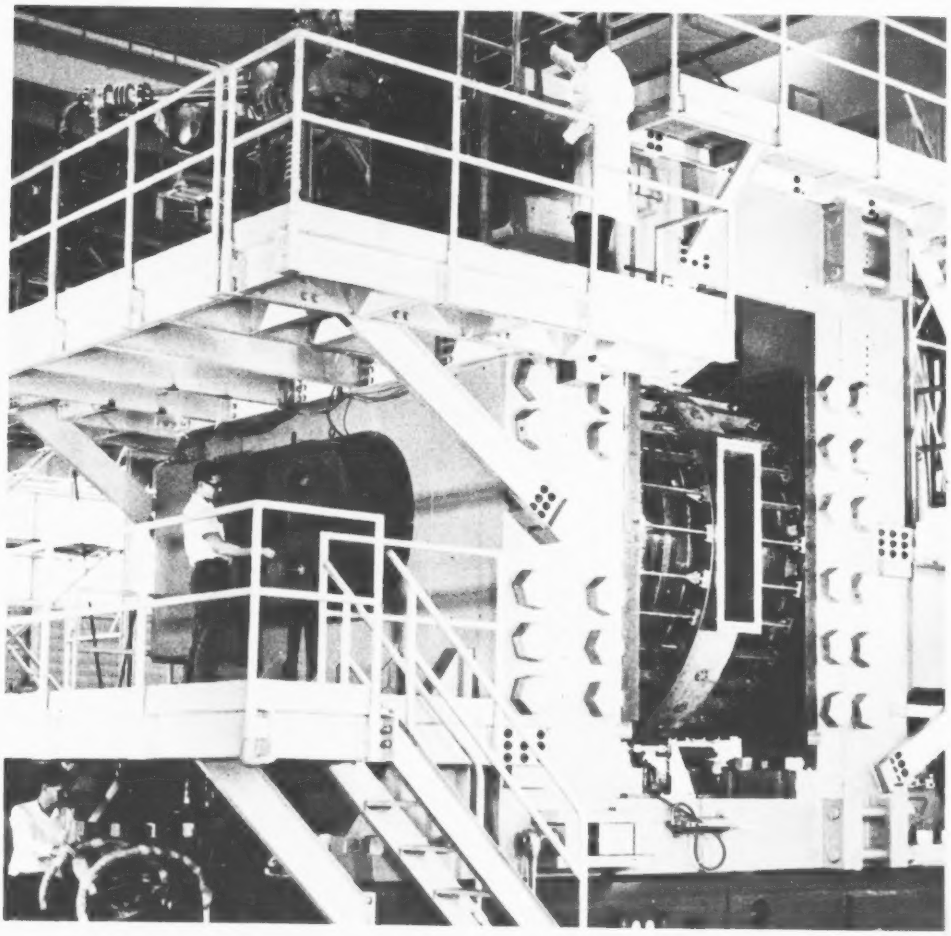
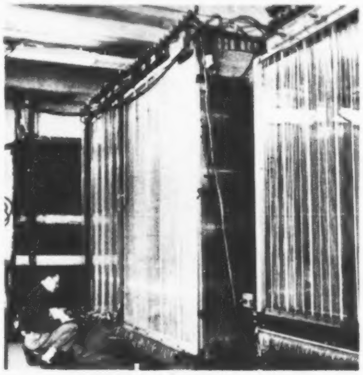


d

particles: they are grouped into "families" according to their properties. Most of these particles exist only very briefly—typical lifetimes are of the order of 10^{-8} second or less. A whole new field, "high-energy physics," has evolved and the high-energy physicist of today is trying to detect some order and structure into which he can fit the large number of "elementary" particles he has discovered.

How do we detect these particles? We have already mentioned a number of methods by which we can observe and measure radioactivity. They include the Geiger counter (Sec. 19.3), the electroscope and electrometer employed since the early days of radioactivity, and the Wilson cloud chamber. In addition we now have various types of ionization chambers, scintillation counters, photographic emulsions, semiconductor devices, bubble chambers and spark chambers, some of which are displayed on these pages. One of the additional units in this course, Elementary Particles, describes the discoveries made with these detection devices.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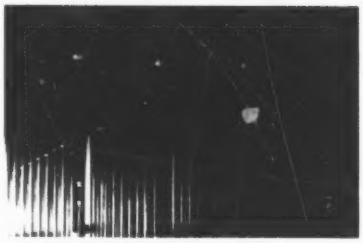
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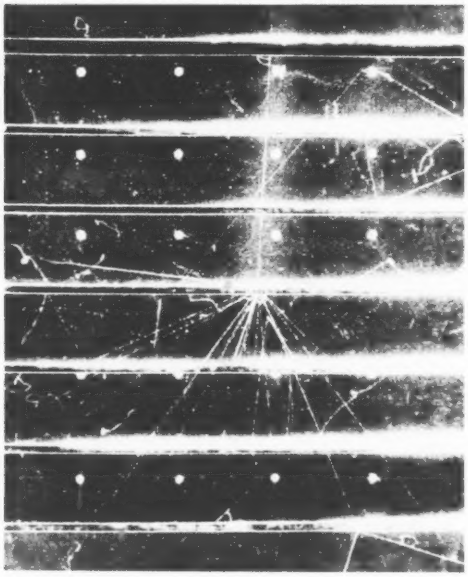
e. The viewing of a projected, enlarged photograph of particle tracks in a bubble chamber.
f. g. h. A spark chamber. A charged particle passing through the chamber ionizes the gas along its path between the plates. When high voltage is applied, sparks jump between the plates along the ionized tracks, thus revealing the paths of the particles.

e

h


Q10 Why can low-energy α particles cause transmutations only in nuclei of low mass?

Q11 Why are protons more effective projectiles for promoting nuclear reactions than α particles or heavy ions?

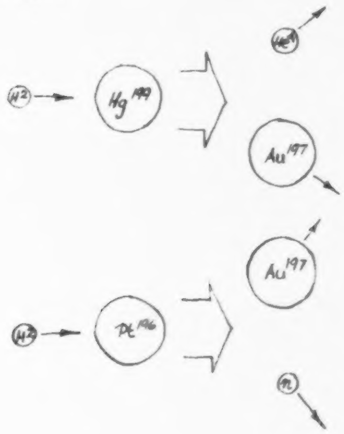
23.8 Nuclear reactions. The development of the cyclotron and other particle accelerators led to great advances in the study of nuclear reactions. Nearly all of the stable nuclides have been bombarded with protons, deuterons, α particles, neutrons and γ rays, and hundreds of nuclear reactions have been examined. Examples of reactions induced by α particles and protons have already been discussed.

Since the first known alchemical writings during the third or fourth centuries A.D., and throughout the historical development of chemistry, the dream of "making gold" has always been present. In most nuclear reactions one element is changed into another: the ancient dream of the alchemist has come true, but it is unlikely to make a fortune for anyone. Now we are finally able to transmute various elements into gold, but such transformations are a far cry, both in method and purpose, from the attempts of the ancient alchemists.

We discuss the transmutation into gold only as an example of a nuclear reaction; a more useful reaction is the transmutation of gold into something else —for example:

$${}_{79}Au^{197} + {}_{0}n^{1} \rightarrow {}_{80}Hg^{198} + {}_{-1}e^{0},$$

which is used to obtain very pure samples of a single mercury isotope.



Gold has only one stable isotope—${}_{79}Au^{197}$; all other gold isotopes are radioactive and are not found in nature. We will illustrate two types of nuclear reactions induced by deuterons, both resulting in gold. One is

$${}_{1}H^{2} + {}_{80}Hg^{199} \longrightarrow {}_{79}Au^{197} + {}_{2}He^{4}.$$

The other is

$${}_{1}H^{2} + {}_{78}Pt^{196} \longrightarrow {}_{79}Au^{197} + {}_{0}n^{1}.$$

In both cases we need an accelerator to produce high-energy deuterons; in bombarding a mercury isotope we produce α particles besides our desired gold. Bombarding platinum we produce neutrons in addition to the gold.

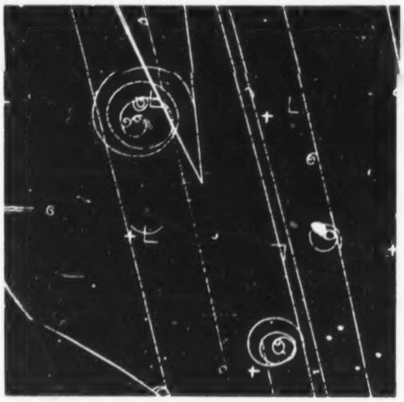
The last reaction, in which a neutron was produced, is an example of reactions which have become especially important because of the usefulness of the neutrons produced. Neutrons can result when nuclei are bombarded with protons, deuterons or α particles, as in the reactions:

$${}_{28}Ni^{58} + {}_{1}H^{1} \rightarrow {}_{29}Cu^{58} + {}_{0}n^{1},$$

$${}_{6}C^{12} + {}_{1}H^{2} \rightarrow {}_{7}N^{13} + {}_{0}n^{1},$$

$${}_{4}Be^{9} + {}_{2}He^{4} \rightarrow {}_{6}C^{12} + {}_{0}n^{1}.$$

The neutrons produced by bombardment can, in turn, be used to induce nuclear reactions. Neutrons are especially effective as "bullets" because they have no electric charge. They are not subject to repulsive electrostatic forces in the neighborhood of a positively charged nucleus, and are therefore more likely to penetrate nuclei than are protons, deuterons or α particles. Because of the neutron's lack of electrical charge many more reactions have been induced by neutrons than by any other kind of particle. Fermi was the first to undertake a systematic program of research involving the use of neutrons as projectiles in nuclear reactions. He bombarded many elements, from the lightest to the heaviest, with neutrons, and studied the properties of the nuclides produced. The research described in the prologue to Unit 1 was done as part of this program.



In this bubble chamber picture, a neutron is produced at bottom center and in turn causes a reaction near the center. (Neutral particles do not leave tracks in bubble chambers.)

A typical neutron-induced reaction, once again resulting in gold, is:

$${}_0n^1 + {}_{80}Hg^{198} \longrightarrow {}_{79}Au^{197} + {}_1H^2.$$

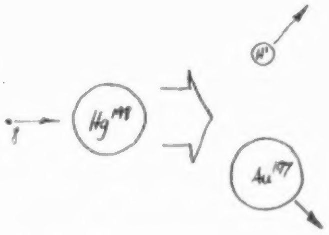
In a very common type of neutron-induced reaction the neutron is captured and a γ ray is emitted, as in the following example:

$${}_0n^1 + {}_{78}Pt^{196} \longrightarrow {}_{78}Pt^{197} + \gamma.$$

Note that since there is no change in the atomic number the element remains the same. An isotope of the target nucleus is produced with a mass number greater by one unit than that of the target nucleus. The new nucleus is produced in an excited state and returns to its lowest energy state by emitting one or more γ rays.

Atomic nuclei can also undergo reactions when bombarded with γ rays; an example, once again resulting in gold, is the reaction:

$$\gamma + {}_{80}Hg^{198} \longrightarrow {}_{79}Au^{197} + {}_1H^1.$$



In this case the energy of the γ ray excites the mercury target nucleus which becomes unstable, ejects a proton and becomes a gold nucleus.

The amount of gold produced by the above reactions is very small; we simply tried to illustrate some typical artificial transmutations. The examples we have given barely suggest the rich variety of such reactions that have been observed.

SG 23.10
SG 23.11

The products of these reactions may change as the energy of the bombarding particles changes. Nuclear reactions are important, not only because they indicate our ability to produce new nuclides, but also because they provide important data about nuclear structure. A model of nuclear structure, to be successful, must enable us to predict the results of these nuclear reactions,just as a successful model of atomic structure must allow us to predict the results of chemical reactions.

Q12 Is this statement true or false: "All nuclear reactions involve transmutation from one element to another"?

Q13 What property of neutrons makes them particularly useful for provoking nuclear reactions?

Q14 Complete the following equation for a nuclear reaction: $_{13}Al^{27} + {}_{1}H^{2} \longrightarrow {}_{0}n^{1} + {}_{?}Si^{?}$.

23.9 Artificially induced radioactivity. In the discussion of nuclear reactions we have passed over an interesting discovery. We have shown that the capture of a neutron by platinum 196 results in platinum 197 and the emission of a γ ray. As seen from Table 22.1 six different isotopes of platinum are found in nature—but platinum 197 is not among these. The question arises: is the platinum 197 produced by neutron capture stable? The answer is no; it is radioactive and decays by the emission of a β particle to gold 197, becoming the only stable gold isotope:

$$_{78}Pt^{197} \longrightarrow {}_{79}Au^{197} + {}_{-1}e^{0} + \bar{\nu} .$$

The half life of platinum 197 is 20 hours.

This is one of the earliest records of a "shower" of electrons and positrons, and shows their tracks curving in opposite directions in a strong magnetic field. The shower was caused by cosmic rays and was recorded in this Wilson cloud chamber photo taken at an altitude of 4.3 km.

The production of radioactive platinum 197 in a nuclear reaction is an example of artificially induced radioactivity, discovered in 1934 by Irène Curie and F. Joliot. They were studying the effects of α particles on the nuclei of light elements. When they bombarded boron, magnesium and aluminum with α particles from polonium, they observed protons and neutrons, as expected. But, in addition to these particles, positive electrons, or positrons, also were observed. The positron is a particle whose mass is the same as that of the electron, and whose charge has the same magnitude but opposite sign to that of the electron.

The positron had been discovered earlier by C. D. Anderson in 1932 while studying photographs of cosmic ray tracks in a cloud chamber. Cosmic rays are highly penetrating radiations which originate outside the earth and consist of protons, electrons, neutrons, photons and other particles. Employing a cloud chamber situated in a magnetic field, Anderson observed some tracks which could have been produced only by particles having the mass and magnitude of charge of the electron, but the curvature was opposite in direction to that of electron tracks; Anderson concluded that the particles producing them must have been positively charged.

The production of positrons along with neutrons as a result of the bombardment of a light element with α particles seemed to indicate that a new type of nuclear reaction could occur in which a neutron and a positron were emitted. But further experiments by Curie and Joliot showed that the light-element targets continued to emit positrons even after the source of the α particles had been removed. When the rate of emission of the positrons was plotted against the time after the removal of the α particle source, curves were obtained, for each target, similar to the curves obtained in natural β radioactivity. The results seemed to show that an initially stable nuclide had been changed into a radioactive one. In the case of the bombardment of ${}_{13}Al^{27}$ by α particles, which produced neutrons as well as the new radioactive material, the reaction expected would produce an isotope of phosphorous:

$$ {}_{13}Al^{27} + {}_{2}He^{4} \xrightarrow{?} {}_{0}n^{1} + {}_{15}P^{30}. $$

Curie and Joliot made chemical separations similar to those made in the study of the naturally radioactive elements, and showed that the target, after bombardment, contained a small amount of phosphorus that was radioactive. Now, phosphorus occurs in nature only as ${}_{15}P^{31}$; natural ${}_{15}P^{31}$ has an isotope abundance of 100 percent and no isotope of phosphorus with mass number 30 had ever been found to occur naturally. It was reasonable to suppose that if P^{30} were made in a nuclear reaction it would be radioactive and would decay in the following manner:

$$ {}_{15}P^{30} \longrightarrow {}_{14}Si^{30} + {}_{1}e^{0} + \nu, $$

where ${}_{14}Si^{30}$ is a known isotope of silicon, ${}_{1}e^{0}$ represents a positron (${}_{-1}e^{0}$ represents an electron), and ν is a neutrino. The half-life of P^{30} turned out to be 2.5 minutes.

F. Joliot and Irene Curie in their laboratory. They were married in 1926.

This kind of β decay implies that a proton in the nucleus is transformed into a neutron and positron (and a neutrino):

$$ {}_{1}p^{1} \longrightarrow {}_{0}n^{1} + {}_{+1}e^{0} + \nu. $$

23.9

After the discovery that the bombardment of light nuclides by α particles can lead to radioactive products, it was found that nuclear reactions induced by protons, deuterons, neutrons and photons can also result in radioactive products. As in the case of the natural radionuclides, an artificial radionuclide can be characterized by its half-life and the type of radiation it emits. When the products of nuclear reactions are radioactive they can be traced in chemical separations by means of their characteristic half-lives or decay products. Otherwise they could not be traced because of the very small amounts involved—often less than a millionth of a gram. The special branch of chemistry that deals with the separation and identification of the radioactive products of nuclear reactions is called radiochemistry and has become an important part of nuclear science. The breadth of this field is indicated by the fact that since 1935 about 1200 artificially radioactive nuclides have been made and identified.

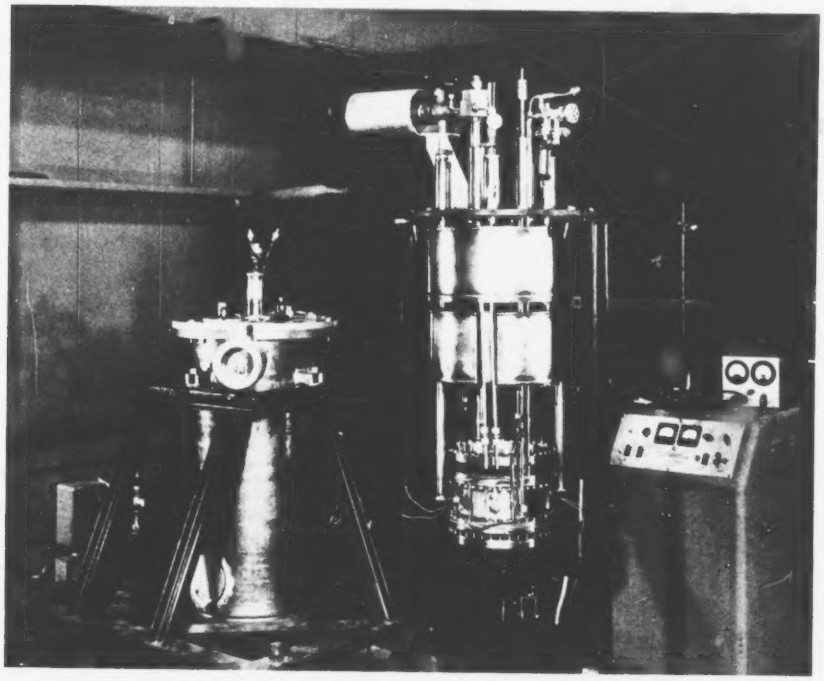
SG 23.12

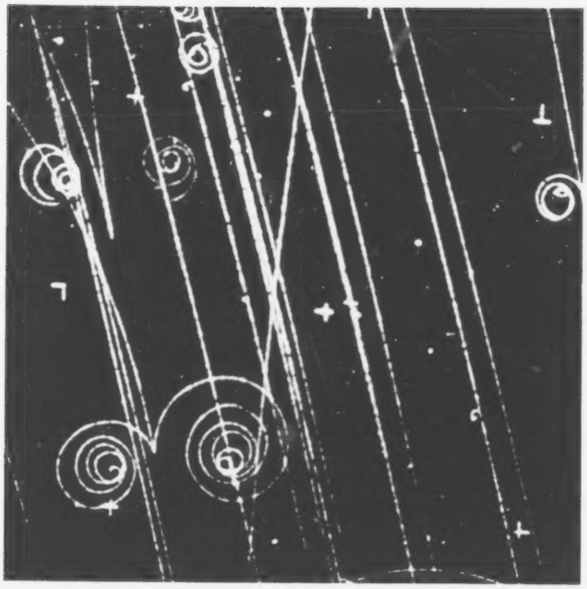
SG 23.13

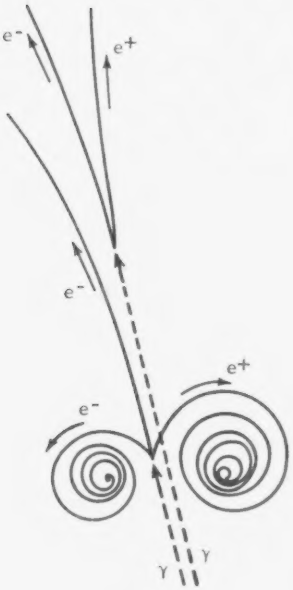
Q15 Complete the following equation for a positive β-decay:

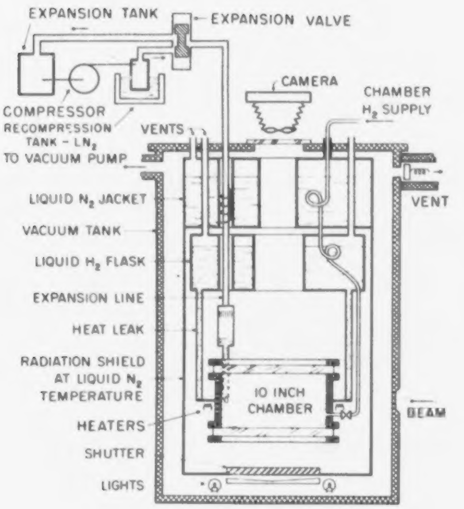
$$_7N^{13} \longrightarrow {}_1e^0 + {}_?C^?$$

How many neutrons and protons were there in the nitrogen nucleus before decay? How many in the carbon nucleus afterward?








EXPANSION TANK
EXPANSION VALVE
CAMERA
CHAMBER H₂ SUPPLY
COMPRESSOR
RECOMPRESSION TANK - LN₂
VENTS
TO VACUUM PUMP
LIQUID N₂ JACKET
VENT
VACUUM TANK
LIQUID H₂ FLASK
EXPANSION LINE
HEAT LEAK
RADIATION SHIELD AT LIQUID N₂ TEMPERATURE
10 INCH CHAMBER
BEAM
HEATERS
SHUTTER
LIGHTS

The bubble chamber photo at the upper left illustrates one of the most important discoveries of modern physics, the interconversion of energy and matter (Chapters 9 and 20). The diagram above shows the significant tracks of that photo. In the upper left an electron-positron pair is formed by a gamma ray (not visible in bubble chamber pictures) interacting with a hydrogen nucleus. An applied magnetic field causes the electron and the positron to be deflected in opposite directions. (Can you determine the direction of the magnetic field?)

In the lower left of the same photo a gamma ray forms another electron-positron pair; the additional electron (third track, upward) was knocked out of a hydrogen atom during this process.

The bubble chamber photo was taken in a 10" liquid hydrogen bubble chamber at the Lawrence Radiation Laboratory of the University of California. The chamber is shown at the far left with the liquid nitrogen shield removed. The accompanying diagram gives some of the details of the bubble chamber and its auxiliary equipment.

23.1 Why would it be difficult to explain $_{92}U^{235}$ as a mixture of alpha particles and electrons?

23.2 On the basis of the proton-electron hypothesis of nuclear composition, how many protons would you expect to find in the $_{92}U^{235}$ nucleus? How many electrons?

23.3 Complete the following nuclear equations:

(a) $_5B^{10} + {_2He^4} \longrightarrow (\quad) + {_1H^1}$.

(b) $_{11}Na^{23} + {_2He^4} \longrightarrow (\quad) + {_1H^1}$.

(c) $_{13}Al^{27} + {_2He^4} \longrightarrow (\quad) + {_1H^1}$.

(d) $(\quad) + {_2He^4} \longrightarrow {_{17}Cl^{35}} + {_1H^1}$.

(e) $(\quad) + {_2He^4} \longrightarrow {_{20}Ca^{42}} + {_1H^1}$.

23.4 Complete the following nuclear equations:

(a) $_3Li^6 + {_1H^1} \longrightarrow {_2He^4} + (\quad)$.

(b) $_4Be^9 + {_1H^1} \longrightarrow {_2He^4} + (\quad)$.

(c) $_4Be^9 + {_1H^1} \longrightarrow (\quad) + {_1H^2}$.

(d) $_5B^{11} + {_2He^4} \longrightarrow {_7N^{14}} + (\quad)$.

23.5 Complete the following nuclear equations:

(a) $Al^{27} + {_0n^1} \longrightarrow Al^{28} + (\quad)$.

(b) $Al^{27} + {_1H^2} \longrightarrow {_1H^1} + (\quad)$.

(c) $Al^{27} + {_1H^1} \longrightarrow {_2He^4} + (\quad)$.

(d) $Al^{27} + {_1H^2} \longrightarrow {_2He^4} + (\quad)$.

What aspect of nuclear reactions do equations (b) and (d) illustrate?

23.6 Explain briefly why the maximum speed gained by nitrogen nuclei in collisions with neutrons is approximately an order of magnitude less than that gained by hydrogen nuclei in collisions with neutrons.

23.7 One major disadvantage of indirect methods of measurement is that the experimental uncertainty is often increased. If Chadwick had measured a maximum speed of 3.2×10^9 cm/sec for hydrogen nuclei (a shift of only 3%), and 4.7×10^8 cm/sec for nitrogen nuclei (no shift), what would be the calculated mass of the neutron? By what percentage would the calculated mass of the neutron change due to the 3% shift in the speed measurement?

23.8 Indicate the mass number A, the atomic number Z, the number of protons and the number of neutrons for each of the following nuclei: (Make a similar table in your notebook.)

	A	Z	protons	neutrons
H^1				
H^2				
He^4				
Li^7				
C^{13}				
U^{238}				
Th^{234}				
Th^{230}				
Pb^{214}				
Pb^{206}				

23.9 How many electrons are there in a neutral atom of

(a) platinum 196?
(b) gold 197?
(c) mercury 198?

23.10 Complete the following nuclear equations:

(a) $_{11}Na^{23} + {}_1H^2 \longrightarrow {}_1H^1 + (\quad)$.

(b) $_{11}Na^{23} + {}_0n^1 \longrightarrow \gamma + (\quad)$.

(c) $_{12}Mg^{24} + {}_0n^1 \longrightarrow {}_1H^1 + (\quad)$.

(d) $_{12}Mg^{26} + {}_1H^2 \longrightarrow {}_2He^4 + (\quad)$.

What aspect of nuclear reactions do these equations illustrate?

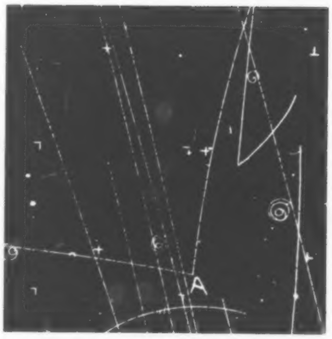
23.11 Describe the following reactions in words:

$$_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{12}Mg^{27} + {}_1H^1.$$

$$_{12}Mg^{27} \longrightarrow {}_{13}Al^{27} + {}_{-1}e^0 + \overline{\nu} + \gamma;\ T = 9.5 \text{ min.}$$

23.12 It is often necessary to infer information in the absence of direct evidence. Thus when a hunter following the tracks of a rabbit in the snow finds that the tracks suddenly stop with no evidence of other tracks or of hiding places, he may infer something about the possible presence of owls or eagles.

The bubble chamber photograph at the right shows, among other things, the tracks of two nuclear particles that originate or terminate at point A. Describe the interaction that occurs at point A in terms of your knowledge of the law of conservation of momentum.



23.13 How do you think the discovery of artifically radioactive nuclides helped the development of theories of nuclear structure?

Chapter 24 Nuclear Energy, Nuclear Forces

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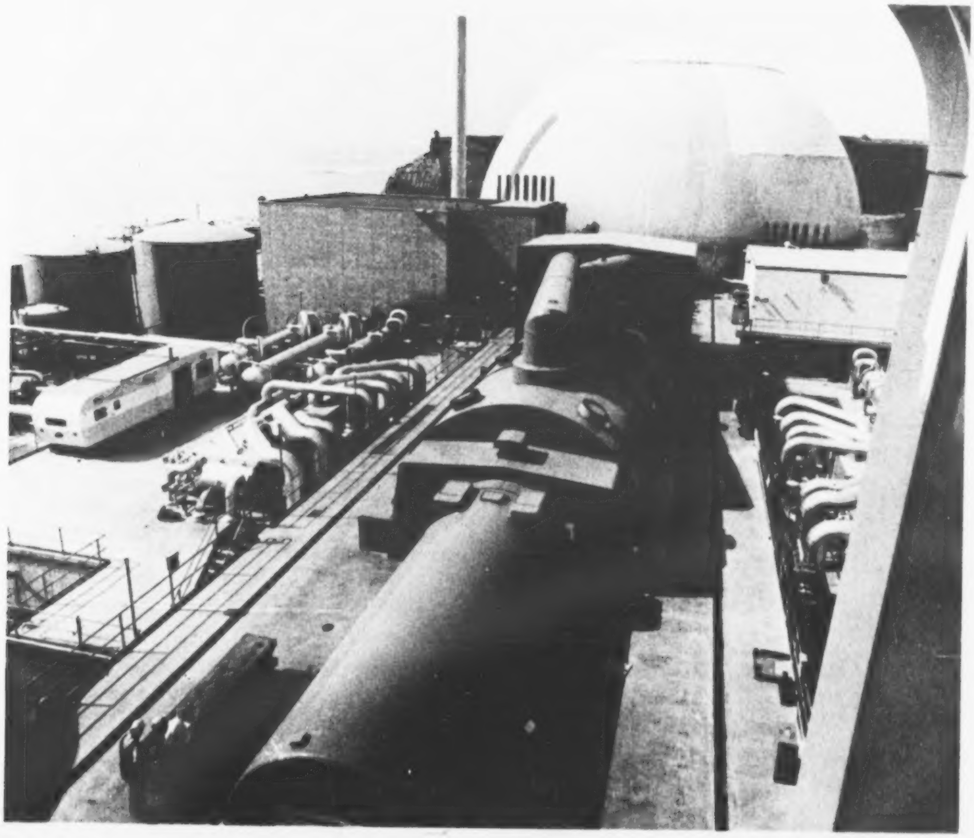


24.1 Conservation of energy in nuclear reactions. In the discussion of nuclear reactions in the last chapter the emphasis was on the transformations of nuclei and on the properties of the nuclides formed. But there is another property of these reactions that is important—the absorption or release of energy. The way in which we wrote the equations for nuclear reactions is analogous to that used for chemical equations, and we can extend the analogy to the treatment of the energy relations in nuclear reactions. In some chemical reactions energy must be supplied from the outside to keep the reaction going, while in others energy is liberated. The formation of water from oxygen and hydrogen is an example of a reaction in which energy is liberated; the reaction between these two gases is usually violent and heat is given off. We may conclude that the water formed has less energy than did the substances of which the water is made. When water is decomposed by electrolysis, electrical energy must be supplied by passing a current through the water, and the products of the reaction —the oxygen and hydrogen liberated—have more energy than the water.

In both cases we neglect the small amount of energy which may be required to start the reaction.

Chemical reactions can be analyzed quantitatively in terms of the amounts of the reacting materials and of the products formed, and in terms of the energy (thermal or electrical) absorbed or liberated. In an analogous way a nuclear reaction can be analyzed in terms of the masses and the energies of the nuclei and particles before and after the reaction. Nuclear reactions may absorb energy or they may liberate energy. The amount of energy absorbed or emitted per nucleus involved is greater by a factor of a million or more than the amount involved per atom in a chemical reaction. Since mass and energy are equivalent, large release of energy will be accompanied by changes in the total rest mass of the interacting nuclei. The relation $E = mc^2$ plays an important part in analyzing nuclear reactions. Nuclear fission and nuclear fusion (discussed later in this chapter) are two special kinds of nuclear reactions in which the energy release is much greater, by a factor of 10 to 100, than that in other nuclear reactions. It is the exceptionally large energy release in these two types of reactions that makes them important in industrial and military applications.

It would be a good idea to reread pp. 102-105 in Unit 5, to review the relativistic relationship of mass and energy. Two important ideas for this chapter are: a) the mass of a moving body is greater than the rest mass by KE/c^2, and b) a particle at rest has a rest energy of m_oc^2.

In this chapter we shall examine the mass and energy relations in nuclear reactions and some of their consequences. This study will show how some of the ideas and experimental information of the last three chapters are linked together.

See "Conservation Laws" in Project Physics Reader 6.

Q1 **Is energy always liberated in a nuclear reaction?**

In this nuclear-electric power plant, a controlled fission reaction supplies heat energy for operation of a steam turbine which drives an electrical generator.

24.2 The energy of nuclear binding. Our concepts of atomic and nuclear structure—that an atom consists of a nucleus surrounded by electrons and that the nucleus is made up of protons and neutrons—led to a fundamental question: is the mass of an atom equal to the sum of the masses of the protons, neutrons and electrons that make up the atom? This question can be answered because the masses of the proton, the neutron and the electron are known, as are the masses of nearly all the atomic species. A survey of the known atomic masses shows that, for each kind of atom, the atomic mass is always less than the sum of the masses of the constituent particles in their free state. The simplest atom containing at least one proton, one neutron and one electron is deuterium, ${}_1H^2$; in this case we have for the masses:

As early as 1927 Aston concluded from his measurements with a mass spectrograph: if two light nuclei combine to form a heavier one, the new nucleus weighs less than the sum of the original ones.

rest mass of one proton = 1.007276 amu
rest mass of one neutron = 1.008665
rest mass of one electron = 0.000549

total rest mass of constituent particles in free state = 2.016490

rest mass of deuterium atom = 2.014102
difference (Δm) = 0.002388 amu.

Although the difference Δm in rest mass may appear small, it corresponds to a significant energy difference because of the factor c^2 in the relation $E = mc^2$. The difference ΔE in energy should correspond to the difference in mass according to the relation: $\Delta E = \Delta mc^2$. The conversion factor from atomic mass (expressed in amu) to energy (expressed in MeV) is

$$1 \text{ amu} = 931 \text{ MeV}.$$

$1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$

$$\begin{aligned}\Delta E &= \Delta mc^2\\ &= (1 \text{ amu})(1.66 \times 10^{-27} \tfrac{\text{kg}}{\text{amu}}) \times (3 \times 10^{8} \tfrac{\text{m}}{\text{sec}})^2\\ &= 14.9 \times 10^{-11} \text{ joules}\\ &= \frac{14.9 \times 10^{-11} \text{ joules}}{1.6 \times 10^{-13} \text{ joules/MeV}}\\ &= 931 \text{ MeV}\end{aligned}$$

If a proton and neutron combine, then a rest mass of 0.002388 amu should be "lost," appearing as 0.002388 amu × 931 MeV/amu = 2.22 MeV of kinetic energy.

The result calculated from the change in rest mass can be compared with the result of a direct experiment. When hydrogen is bombarded with neutrons, a neutron can be captured in the reaction:

$${}_0n^1 + {}_1H^1 \longrightarrow {}_1H^2 + \gamma.$$

Since there are no fragments with large kinetic energy, the "missing" mass of 0.002388 amu must be carried away by the γ radiation. The energy of the γ ray has been determined, and is 2.22 MeV, as predicted! The inverse reaction, in which deuterium is bombarded with γ rays, has also been studied:

$${}_1H^2 + \gamma \longrightarrow {}_1H^1 + {}_0n^1 .$$

When the energy of the γ rays is less than 2.22 MeV, no reaction occurs. But if we use γ rays of energy 2.22 MeV or greater, the reaction does occur: a proton and a neutron are detected. In the "capture" of a neutron by the nucleus ${}_1H^1$, energy is liberated. In the inverse reaction (${}_1H^2$ bombarded with γ rays) energy is absorbed. The energy, 2.22 MeV, is called the binding energy of the deuteron. It is the energy released when a proton and neutron combine to form a nucleus. (The binding energy is also, therefore, the amount of energy which would be needed to break the deuteron up again.)

Q2 When energy is "liberated" during a nuclear reaction, what becomes of it?

24.3 Stability and binding energy. The calculation made for deuterium can be extended to the other nuclear species. In practice, physicists make such calculations for atoms rather than for atomic nuclei, because experimental values of atomic masses are known from mass-spectrographic measurements. Since an atom contains electrons (in the outer shells) as well as the protons and neutrons in the nucleus, the mass of the electrons must be included in the calculations. It is convenient to do so by combining the mass of one proton and one electron and using the mass of one hydrogen atom for the combination. (The binding energy and equivalent mass involved in the formation of a hydrogen atom from a proton and an electron may be neglected—it is only 13 eV as compared to nuclear binding energies which are several MeV per nuclear particle.) The following example illustrates the calculations necessary to find the binding energy of an atom. We compare the actual mass of a carbon 12 atom with the total mass of its separate component particles:

rest mass of 6 hydrogen atoms (includes 6 protons and 6 electrons)	6 × 1.007825	= 6.046950 amu
rest mass of 6 neutrons	6 × 1.008665	= 6.051990
total rest mass of particles		12.098940
rest mass of carbon 12		12.000000
difference in rest mass		Δm = 0.098940 amu

$$0.098940 \text{ amu} \times 931 \text{ MeV/amu} = 92.1 \text{ MeV}.$$

SG 24.1

In the same manner one can calculate the binding energy of any stable atom. Figure 24.1a shows how the binding energy for stable nuclides increases with increasing atomic mass, as more particles are added to the nucleus. Such data have important implications for the structure of the nucleus. This can be seen more clearly if we calculate the average binding energy per particle. In the case of carbon 12 example, we found the total binding energy to be 92.1 MeV. Since we are dealing with 12 particles inside the nucleus (6 protons and 6 neutrons), the average binding energy per particle is 92.1 MeV/12 or 7.68 MeV. In Fig. 24.1b the values of average binding energy per particle (in MeV) are plotted against the number of particles (mass number A).

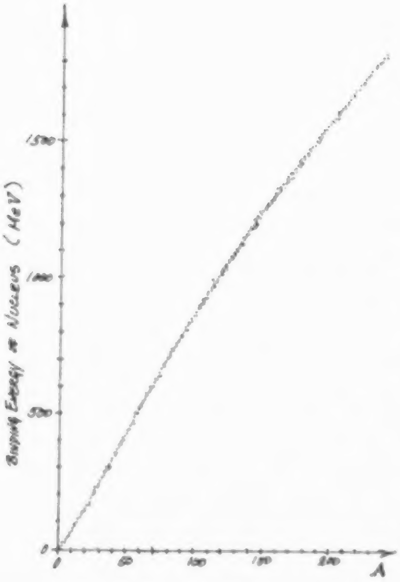
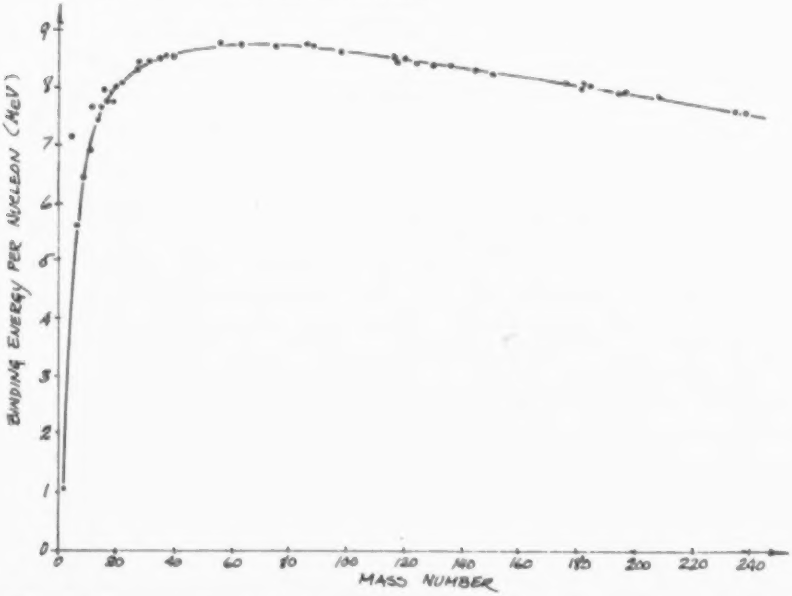


Fig. 24.1a Binding energy as a function of A.

The binding energy per particle starts with a low value for deuterium, and then increases rapidly. Some nuclei, for example He^4, C^{12} and O^{16} have exceptionally high values as compared with their neighbors. More energy would have to be supplied to remove a particle from one of them than from one of their neighbors. We would therefore expect He^4, C^{12} and O^{16} to be exceptionally stable. There is evidence in favor of this conclusion: for example, the fact that the four particles making up the He^4 nucleus are emitted as a single unit, the α particle, in radioactivity. The curve has a broad maximum extending from approximately A = 50 to A = 90 and then drops off for the heavy elements. Thus, $_{29}Cu^{63}$ has a binding energy per particle of about 8.75 MeV, while $_{92}U^{235}$, near the high-A end of the curve, has a value of 7.61 MeV. The nuclei in the neighborhood of the maximum of the curve, for example, those of copper, should be more difficult to break up than those of uranium.

SG 24.2



Notice the unusually high position of He^4 (the dot near 7.1 MeV). This is related to its unusually great stability.

Fig. 24.1b Average binding energy per particle as a function of the number of particles A.

Now it is clear why atomic masses are not exactly whole number multiples of the mass of a hydrogen atom, even though nuclei are just collections of identical protons and neutrons. The total rest mass of a combination of these particles is reduced by an amount corresponding to the binding energy, and the average binding energy varies from nuclide to nuclide.

With the information we now have about the nuclear binding energy, we shall be able to get an understanding of the energy relations in nuclear reactions. (There are other important implications of the average binding energy curve, Fig. 24.1b which we shall mention later.)

Q3 Which would be more stable, a nuclide with a high total binding energy, or a nuclide with a high average binding energy?

24.4 The mass-energy balance in nuclear reactions. In the previous section we used a very simple nuclear reaction to introduce the concept of binding energy. In this section we shall use a more complicated reaction—one in which the products are nuclei—to show an important relation between the binding energy and the energy liberated in a nuclear reaction.

We shall analyze the mass-energy balance in the reaction of a proton with lithium 7:

$$_1H^1 + {_3Li^7} \longrightarrow {_2He^4} + {_2He^4} \,.$$

This reaction has historical interest: it was the first case of a nuclear disintegration brought about by artificially accelerated particles; and the analysis of the reaction provided one of the earliest quantitative tests of Einstein's mass-energy relation. The reaction was a good one to analyze because the masses of the proton, the α particle and the Li atom were known, and the kinetic energies of the proton and the two α particles could be measured accurately. The values of the atomic masses are:

rest mass of Li^7 = 7.016005 amu
rest mass of H^1 = 1.007825 amu
rest mass of He^4 = 4.002604 amu

The energy released may be calculated by finding the difference in rest masses before and after the nuclear reaction takes place. The difference in rest mass is 0.018622 amu, corresponding to 17.3 MeV. Since total energy is conserved, we can assume that 17.3 MeV of lost rest energy appears in the total kinetic energy of the two α particles emitted. In actual experiments the incident proton has kinetic energy so that the 17.3 MeV represents the difference between the kinetic energies of the two emitted α particles

before		after	
Li^7	7.016005	He^4	4.002604
H^1	1.007825	He^4	4.002604
	8.023830		8.005208

$$\begin{array}{r} 8.023830 \\ -\ \underline{8.005208} \\ \Delta m = 0.018622 \text{ amu} \end{array}$$

$$0.018622 \text{ amu} \times 931 \text{ MeV/amu} = 17.3 \text{ MeV}$$

and the kinetic energy of the incident proton. The agreement between the energy calculated from the masses and the experimental value found from the kinetic energies shows that the mass-energy relation is valid. There is a genuine release of energy from the lithium atom at the expense of some of the rest mass of its fragments. This experiment was first done in 1932. Since then hundreds of nuclear transformations have been studied and the results have invariably agreed with the mass-energy relationships calculated by means of Einstein's equation $E = mc^2$.

The results obtained for the mass-energy balance in nuclear reactions can be related to information about binding energy contained in Fig. 24.1b. For example, the binding energy per particle of the lithium 7 nucleus ${}_3Li^7$ is 5.6 MeV. Since lithium 7 has seven particles in the nucleus, the total binding energy is 5.6 × 7 or 39.2 MeV, while the incident proton has no binding energy. The total binding energy of each α particle (He^4 nucleus) is 28.3 MeV; a total of 56.6 MeV for the two α particles. Since the nucleons in the product fragments are more tightly bound by 56.6—39.2 = 17.4 MeV, there will be 17.4 MeV of energy released in the reaction, appearing as kinetic energy of the fragments. This checks with the increase in kinetic energy found experimentally.

Since binding energy is the energy released in the formation of a nucleus, those nuclei with the highest binding energy have lost the most rest energy.

Analysis of many nuclear reactions verifies the general rule: *When the total binding energy of the products exceeds that of the reactants, energy is liberated*. That is, whenever the products of a nuclear reaction lie higher on the average binding energy curve, they have greater binding energy per particle and so energy is released in their formation.

The shape of the average binding energy curve indicates that there are two general processes which can release energy from nuclei: combining light nuclei into a more massive nucleus, or splitting up heavy nuclei into nuclei of medium mass. In either process the products would have greater average binding energy, so energy would be released. A process in which two nuclei join together to form a heavier nucleus is called *nuclear fusion*. A process in which a heavy nucleus splits into fragments of intermediate mass is called *nuclear fission*. Both fusion and fission have been shown to occur. Both processes can be made to take place slowly (as in a nuclear power plant) or very rapidly (as in a nuclear explosion).

Q4 Would breaking very heavy nuclei up into very light nuclei result in the liberation of energy?

24.5 Nuclear fission: discovery. The discovery of nuclear fission is an example of an unexpected result of great practical importance, obtained during the course of research carried on for reasons having nothing to do with the possible usefulness of the discovery. It is also an excellent example of the combined use of physical and chemical methods in nuclear research. After Joliot and Curie showed that the products of nuclear reactions could be radioactive, Fermi and his colleagues in Italy undertook a systematic study of nuclear reactions induced by neutrons. One of the purposes of this research was to produce new nuclides. Indeed, many new radioactive nuclides were made and their half-lives were determined. The kind of nuclear reaction used most successfully in this study was the capture of a neutron with the emission of a γ ray as discussed in Sec. 23.7. For example, when aluminum is bombarded with neutrons, the following reaction occurs:

A few of the problems encountered by Fermi in his work on these reactions were related in the Prologue to Unit 1.

$$_0n^1 + {}_{13}\mathrm{Al}^{27} \longrightarrow {}_{13}\mathrm{Al}^{28} + \gamma \; .$$

Aluminum 28 is radioactive with a half-life of 2.3 minutes and decays by β emission into silicon:

$$_{13}\mathrm{Al}^{28} \longrightarrow {}_{14}\mathrm{Si}^{28} + {}_{-1}e^0 + \bar{\nu} \; .$$

As a result of the two reactions a nuclide is produced with values of Z and A each greater by one unit than those of the initial nucleus. Fermi thought that if uranium (the atomic species having the largest known value of Z) were bombarded with neutrons, a new element might be formed by the β decay of the heavier uranium isotope:

$$_0n^1 + {}_{92}\mathrm{U}^{238} \longrightarrow {}_{92}\mathrm{U}^{239} + \gamma \; ,$$

$$_{92}\mathrm{U}^{239} \longrightarrow {}_{93}(?)^{239} + {}_{-1}e^0 + \bar{\nu} \; .$$

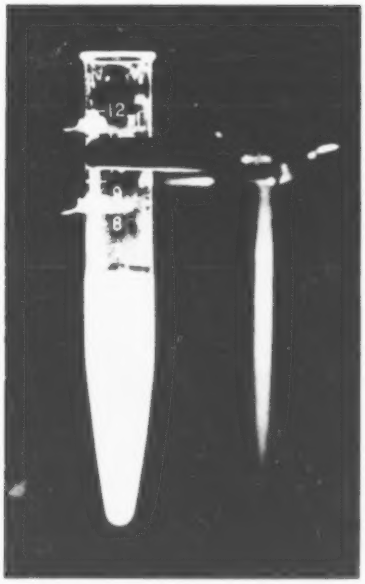
SG 24.7

If the new nuclide denoted by $_{93}(?)^{239}$ were also to emit a β:

$$_{93}(?)^{239} \longrightarrow {}_{94}(?)^{239} + {}_{-1}e^0 + \bar{\nu} \; .$$

In this way, two new elements might be produced (with Z = 93 and 94). If these reactions could be made to occur, the result would be the man-made production of an element, or elements, not previously known to exist—transuranium elements.

Fermi found in 1934 that the bombardment of uranium with neutrons actually produced several new half-lives in the target; these were attributed to traces of new-formed transuranium elements.



By bombarding heavy elements with a variety of particles it has been possible to create artificially a series of transuranium elements. Those elements, up to Z = 103, are listed below. A tiny sample of one of them, curium 244—dissolved in a test tube of water, is shown in the 5-minute exposure above.

$_{92}U$	Uranium
$_{93}Np$	Neptunium
$_{94}Pu$	Plutonium
$_{95}Am$	Americium
$_{96}Cm$	Curium
$_{97}Bk$	Berkelium
$_{98}Cf$	Californium
$_{99}Es$	Einsteinium
$_{100}Fm$	Fermium
$_{101}Md$	Mendelevium
$_{102}No$	Nobelium
$_{103}Lw$	Lawrencium

The results aroused much interest, and in the next five years a number of workers experimented with the neutron bombardment of uranium. Many different radioactive half-lives were discovered, but attempts to identify these half-lives with particular elements led to great confusion. The methods used were similar to those used in the study of the natural radioactive elements. A radioactive nuclide formed in a nuclear reaction is usually present in the target area only in an extremely small amount, possibly as little as 10^{-12} grams, and special techniques to separate these small quantities had to be developed.

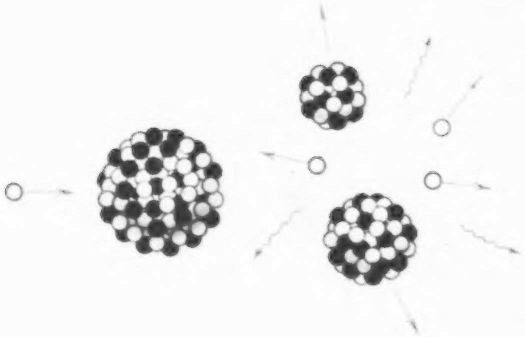
The reason for the confusion was found early in 1939 when Otto Hahn and Fritz Strassmann, two German chemists, showed definitely that one of the supposed transuranium elements was actually an isotope of barium ($_{56}Ba^{139}$), identified by its half-life of 86 minutes and its chemical behavior. Another nuclide resulting from the neutron bombardment of uranium was identified as lanthanum ($_{57}La^{140}$) with a half-life of 40 hours.

The production of the nuclides $_{56}Ba^{139}$ and $_{57}La^{140}$ from uranium, which has the atomic number 92 and an atomic mass of nearly 240, required an unknown kind of nuclear reaction in which the uranium nucleus is split almost in half. If such a process really occurred, it should also be possible to find "the other half," that is, to find nuclides with mass between 90 and 100 and atomic numbers of about 35. Hahn and Strassmann were able to find a radioactive isotope of strontium ($Z = 38$) and one of yttrium ($Z = 39$) which fulfilled these conditions, as well as isotopes of krypton ($Z = 36$) and xenon ($Z = 54$). It was clear from the chemical evidence that the uranium nucleus, when bombarded with neutrons, can indeed split into two nuclei of intermediate atomic mass.

Although Hahn and Strassmann showed that isotopes of intermediate mass did appear, they hesitated to state the conclusion that the uranium nucleus could be split into two large parts. In their report dated January 9, 1939, they said:

> On the basis of these briefly presented experiments, we must, as chemists, really rename the previously offered scheme and set the symbols Ba, La, Ce in place of Ra, Ac, Th. As "nuclear chemists" with close ties to physics, we cannot decide to make a step so contrary to all existing experience of nuclear physics. After all, a series of strange coincidences may, perhaps, have led to these results.

The step which Hahn and Strassmann could not bring themselves to take was taken on January 16, 1939 by two Austrian physicists, Miss Lise Meitner and Otto R. Frisch. They



Schematic diagram representing uranium fission.

suggested that the neutron initiated a decomposition of the uranium nucleus into "two nuclei of roughly equal size," a process which they called "nuclear fission" after the division, or fission, of a living cell into two parts. They predicted that the fragments would have great kinetic energy and would be radioactive. The predictions of Meitner and Frisch were soon verified experimentally. Shortly afterward, it was found that transuranium elements also are formed when uranium is bombarded with neutrons. In other words the capture of a neutron by uranium sometimes leads to fission, and sometimes leads to β decay. The β decay results in the formation of isotopes of elements of atomic number 93 and 94—later named neptunium and plutonium. The mixture of the two types of reaction, fission and neutron capture, followed by β decay, was responsible for the difficulty and confusion in the analysis of the effects of bombarding uranium with neutrons. The experiments opened two new fields of scientific endeavor: the physics and chemistry of the transuranium elements and the study and use of nuclear fission.

Lise Meitner and Otto Hahn

Lise Meitner, born in Austria, joined Otto Hahn in 1908 in a research collaboration that lasted thirty years. In 1938, Miss Meitner was forced to leave Germany. She was in Sweden when she published the first report on fission with her nephew, O. R. Frisch.

The discovery of nuclear fission inspired research workers all over the world and much new information was obtained within a short time. It was found that a uranium nucleus, after capturing a neutron, can split into one of more than 40 different pairs of fragments. Radiochemical analysis showed that nuclides result with atomic numbers from 30 to 63 and with mass numbers from 72 to 158. Neutrons also are emitted in fission; the average number of neutrons emitted is usually between 2 and 3. (Under appropriate conditions these neutrons can, in turn, cause fission in neighboring uranium atoms, and a process known as a chain reaction can develop in a sample of uranium.) The following reaction indicates one of the many ways in which a uranium nucleus can split:

$$ {}_0n^1 + {}_{92}U^{235} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\ {}_0n^1 \ . $$

Otto Frisch

SG 24.8

SG 24.9

The nuclides ${}_{56}\mathrm{Ba}^{141}$ and ${}_{36}\mathrm{Kr}^{92}$ are not found in nature and are not stable; they are radioactive and decay by β emission. For example, ${}_{56}\mathrm{Ba}^{141}$ can decay into ${}_{59}\mathrm{Pr}^{141}$ by successive emission of three β particles, as shown by the following scheme (in which the numbers in parentheses are the half-lives):

$${}_{56}\mathrm{Ba}^{141} \xrightarrow[(18\text{ min})]{{}_{-1}e^{0}} {}_{57}\mathrm{La}^{141} \xrightarrow[(3.6\text{ hr})]{{}_{-1}e^{0}} {}_{58}\mathrm{Ce}^{141} \xrightarrow[(32\text{ days})]{{}_{-1}e^{0}} {}_{59}\mathrm{Pr}^{141}$$

Similarly, ${}_{36}\mathrm{Kr}^{92}$ is transformed into ${}_{40}\mathrm{Zr}^{92}$ by four successive β decays.

Only certain nuclides can undergo fission. For those which can, the probability that a nucleus will split depends on the energy of the neutrons used in the bombardment. The nuclides ${}_{92}\mathrm{U}^{235}$ and ${}_{94}\mathrm{Pu}^{239}$ can undergo fission when bombarded with neutrons of any energy, from a small fraction of an electron volt, say 0.01 eV or less, up. On the other hand, U^{238} and Th^{232} undergo fission only when bombarded with neutrons having kinetic energies of 1 MeV or more. The latter nuclides, which have even Z and even A, are less likely to undergo fission than are uranium 235 and plutonium 230 which have even Z and odd A. Such information is very helpful in trying to construct the nuclear models to be discussed in Sec. 24.11, 12.

Plutonium 239 (${}_{94}\mathrm{Pu}^{239}$) is produced by the capture of a neutron by ${}_{92}\mathrm{U}^{238}$ and the subsequent emission of two β particles, as discussed on p. 89.

The energy released in the fission reaction is about 200 MeV. This value can be calculated either directly from the atomic masses or from the average binding energy curve of Fig. 24.1b. The energy release is much larger than in the more common nuclear reactions (usually less than 10 MeV). The combination of the large energy release in fission and the possibility of a chain reaction is the basis of the large-scale use of nuclear energy.

Q5 **What two reactions resulted in the appearance of a transuranium element?**

Q6 **What product of fission makes a chain reaction possible?**

24.6 Nuclear fission: controlling chain reactions. For a chain reaction to continue at a constant level, it is necessary that there be a favorable balance between the net production of neutrons by fissions and the loss of neutrons due to the following three processes:

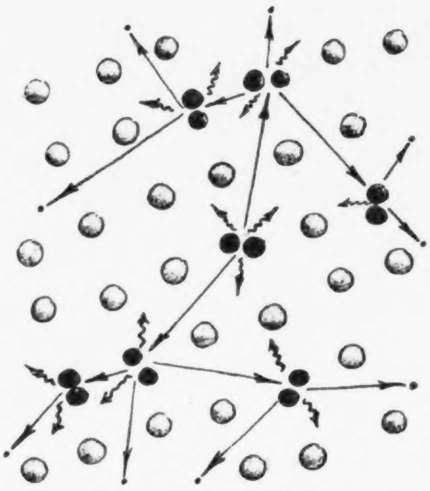
(1) capture of neutrons by uranium not resulting in fissions;

(2) capture of neutrons by other materials;

(3) escape of neutrons without being captured.

If too many neutrons escape or are absorbed, there will not be enough to sustain the chain reaction. If too few neutrons escape or are absorbed, the reaction will build up. The design of nuclear reactors as energy sources involves finding proper sizes, shapes, and materials to maintain a balance between neutron production and loss.

Since the nucleus occupies only a tiny fraction of an atom's volume, the chance of a neutron's colliding with a uranium nucleus is small and a neutron can pass through billions of uranium (or other) atoms while moving a few inches. If the assembly is small, a significant percentage of the fission neutrons can escape from the assembly without causing further fissions. The leakage of neutrons can be so large that a chain reaction cannot be sustained. If the assembly is made larger, a smaller percentage of the neutrons escape, or leak out: if the assembly were infinitely large, this fraction would approach zero. For a given combination of materials—uranium and other materials which may be needed—there is a size, called the critical size, for which the net production of neutrons by fission is just equal to the loss of neutrons by nonfission capture and leakage. If the size of the assembly is smaller than this critical size, a chain reaction cannot be sustained. The determination of the materials and their arrangement with which a reasonable critical size can be obtained is an important part of research in the new field of "nuclear engineering."

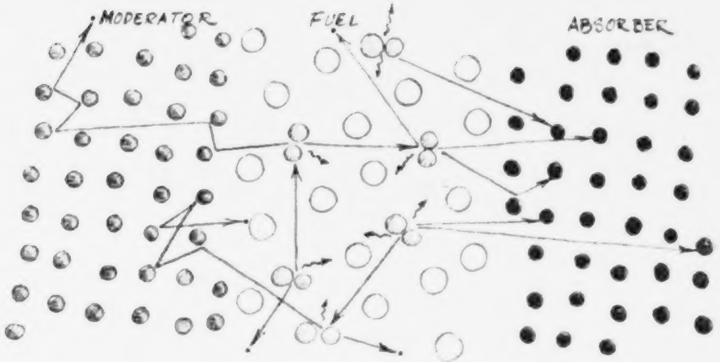

A schematic diagram of the beginning of a chain reaction. The nucleus in the center has fissioned into 2 parts, releasing gamma rays and neutrons. Some of the neutrons are captured by other nuclei, promoting further fissioning with the accompanying release of more neutrons.... and so on.

SG 24.10

Another important problem in the design of nuclear reactors arises from the fact that fission is much more probable when U^{235} is bombarded with slow neutrons than when it is bombarded with fast neutrons. Although nuclear reactors can be built in which the fissions are induced by fast neutrons, it has been easier to build reactors in which the fissions are induced by slow neutrons. The neutrons released in fission have kinetic energies from about 0.01 MeV to nearly 20 MeV, with an average kinetic energy of about 2 MeV. The fast fission neutrons can be slowed down if the uranium is mixed with a material to which the neutrons can lose energy in collisions. The material should be relatively low in atomic mass so that the neutrons can transfer a significant fraction of their energy in elastic collisions; but the material should not absorb many neutrons. Carbon in the form of graphite, and also water, heavy water and beryllium meet these requirements. These substances are called moderators because they slow down—moderate—the newly produced neutrons to energies at which the probability of causing additional fission is high.

See "Success" in Project Physics Reader 6.

Fig. 24.2 Schematic diagram of processes in a nuclear reactor.



Hydrogen atoms in water are very effective in slowing down neutrons because the mass of a hydrogen nucleus is nearly the same as that of a neutron and because the number of hydrogen atoms per unit volume is high. A neutron can lose a large fraction of its energy in a collision with a hydrogen nucleus and only about 15 to 20 collisions are needed, on the average, to slow down the neutron to energies of 1 eV or less. However, the use of hydrogen has the disadvantage that the probability of the reaction

$${}_1H^1 + {}_0n^1 \longrightarrow {}_1H^2 + \gamma$$

is large enough so that too many neutrons may be absorbed by the hydrogen. In fact, it has been found impossible to achieve a chain reaction with natural uranium and water.

Heavy water: $(H^2)_2O$, or D_2O.

On the other hand, the absorption of a neutron by a deuterium nucleus in heavy water

$${}_1H^2 + {}_0n^1 \longrightarrow {}_1H^3 + \gamma$$

has an extremely small probability. A chain reaction can therefore be achieved easily with natural uranium and heavy water. Reactors with natural uranium as the fuel and heavy water as the moderator have been built in the United States, Canada, France, Sweden, Norway and other countries.

The contrast between the nuclear properties of hydrogen and deuterium has important implications for the development of nuclear reactors. Heavy water (D_2O) is much more expensive than ordinary water (H_2O) but, when it is used with natural uranium (mostly U^{238}) a chain reaction can be achieved efficiently. Ordinary water can be used, nonetheless, if uranium enriched in the isotope U^{235} is used instead of natural uranium. Many reactors "fueled" with enriched uranium and with ordinary water have been built in the United States. In fact, this general reactor type has been used in nearly all the large nuclear power plants built so far and in the reactors used in nuclear-powered submarines.

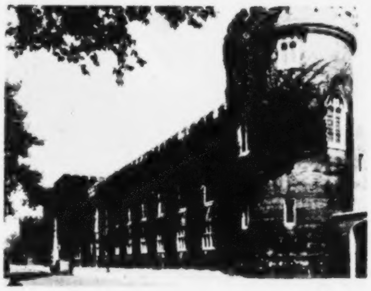
Carbon in the form of graphite has been used as a moderator in many reactors, including the earliest ones. It is not as good a slowing-down agent as water or heavy water: about 120 collisions with carbon atoms are needed to slow fission neutrons with an average energy of 2 MeV to the energy of about 0.025 eV desired; in heavy water only about 25 collisions are needed, and in water about 15. Although carbon in the form of graphite is not the best moderator and absorbs some neutrons, it does permit a chain reaction to occur when lumps of natural uranium (cylindrical rods, for example) are suitably arranged in a large mass of graphite. The rods must be of appropriate size and must be suitably spaced throughout the graphite. The determination of just how this could be done was one of the main problems that had to be solved before the first chain reaction could be achieved, in 1942 at the University of Chicago. Many graphite-moderated reactors are now in operation throughout the world.

The control of a reactor is relatively simple. If fission is occurring too frequently a few "control" rods are inserted into the reactor. The rods consist of a material (such as cadmium or boron) that absorbs slow neutrons, thereby reducing the number of neutrons in the moderator. Removal of the control rods will allow the reaction to speed up. Fig. 24.2 is a schematic diagram of the main processes that occur in a nuclear reactor in which uranium is the fissionable material.

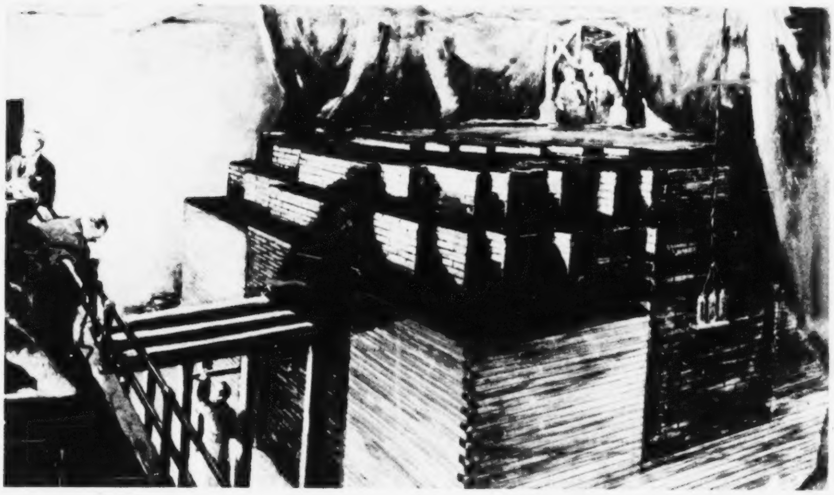
Q7 What is a "moderator?"

Q8 What is an advantage and a disadvantage of using water as a moderator in nuclear reactors?

ON DECEMBER 2, 1942
MAN ACHIEVED HERE
THE FIRST SELF-SUSTAINING CHAIN REACTIO
AND THEREBY INITIATED THE
CONTROLLED RELEASE OF NUCLEAR ENERGY



The west wall of the football stands of Stagg Field. Squash courts under these stands were used as the construction site of the first nuclear reactor. Below is an artist's sketch of that graphite-moderated reactor as it first became self-sustaining.



24.7 Nuclear fission: large-scale energy release and some of its consequences.

The large-scale use of nuclear energy in chain reactions was accomplished in the United States between 1939 and 1945. The work was done under the pressure of World War II, as a result of the cooperative efforts of large numbers of scientists and engineers. The workers in the U.S. included Americans, Britons and European refugees from fascist-controlled countries. The energy was used in two forms: in the so-called atomic bomb, in which an extensive chain reaction occurs in a few millionths of a second; and in the nuclear reactor, in which the operating conditions are so arranged that the energy from fission is released at a much slower and steadier rate. In the nuclear reactor the fissionable material is mixed with other materials in such a way that, on the average, only one of the neutrons emitted in fission causes the fission of another nucleus; in this way the chain reaction just sustains itself. In a nuclear bomb the fissionable material is unmixed (that is, pure) and the device is designed so that nearly all of the neutrons emitted in each fission cause fissions in other nuclei.

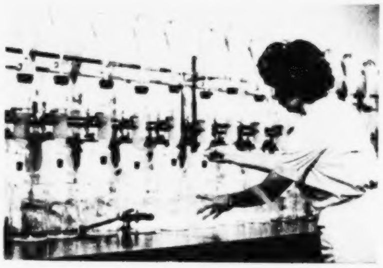
It was essentially an applied engineering problem rather than a research problem in physics. Analogous work was known to be in progress in Nazi Germany

Nuclear reactors were used during World War II to manufacture Pu^{239} from U^{238}. They were designed in such a way that some of the neutrons from the fission of U^{235} were slowed down enough so that they would not cause fission of U^{238} but, instead, were absorbed by the U^{238} to form Pu^{239} through the reactions described in the previous section. A single nuclear bomb, using U^{235}, destroyed the city of Hiroshima, Japan, on August 6, 1945; another bomb, using ${}_{94}Pu^{239}$, destroyed the city of Nagasaki three days later, just prior to the surrender of Japan and the end of World War II.

Since the end of World War II in 1945, the use of nuclear energy from fission has been developed in two different directions. One direction has been military. Other countries besides the United States have made nuclear weapons, namely, the United Kingdom, the Soviet Union, France, and China. The enormous death-dealing capability of these weapons and the ever-larger numbers of bombs that have been accumulating have increased and made more dangerous the tension throughout the world and have emphasized the need for the peaceful settlement of international disputes.

Scientists have been prominently involved in activities to alert their government and fellow citizens to the moral and practical problems raised by the nuclear weapons race.

One incidental problem has been that of the radioactive fallout from bomb tests. The explosion of a nuclear bomb liberates very large amounts of radioactive materials. These materials can be blown by winds from one part of the world to another and carried down from the atmosphere by rain or snow. Some of the radioactivities are long-lived; the materials may be absorbed in growing foodstuffs and eaten by animals and people. It is known that under certain conditions radioactive materials can cause harmful genetic effects as well as somatic effects. One of the most abundant and long-lived products of the fission of U^{235} and Pu^{239} is strontium 90 ($_{38}Sr^{90}$). This isotope of strontium is similar to $_{20}Ca^{40}$ in its chemical properties. Hence when Sr^{90} is taken into the body, it finds its way into bone material. It decays by emission of 0.54-MeV β particles (half-life = 28 years). If present in large quantities it can cause leukemia, bone tumor, and possibly other forms of damage, particularly in growing children. There has been much research and discussion of the possibility of damage to present and future generations. As a result, the United States, the United Kingdom, the Soviet Union and most other nations agreed, in 1963, to a moratorium on further bomb tests in the atmosphere.



A technician checking milk samples for radioactivity.

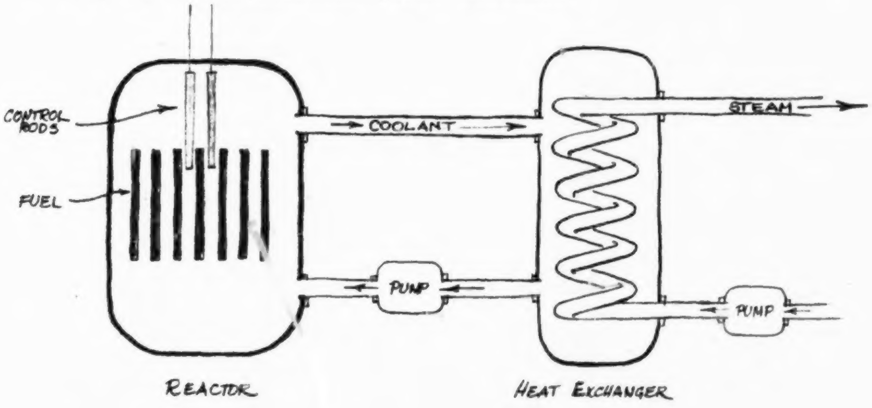
Genetic effects of radiation: effects producing changes in cells which will affect offspring of exposed individual.

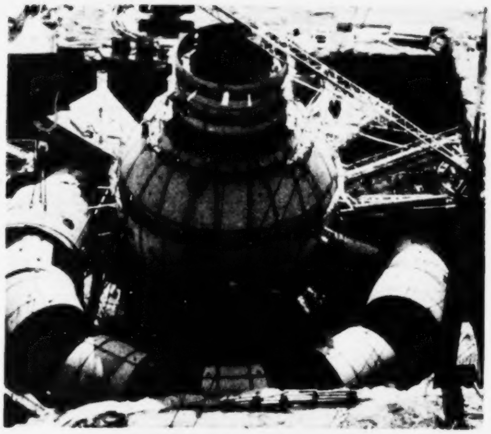
Somatic effects: all effects caused by radiation to an individual during his lifetime.

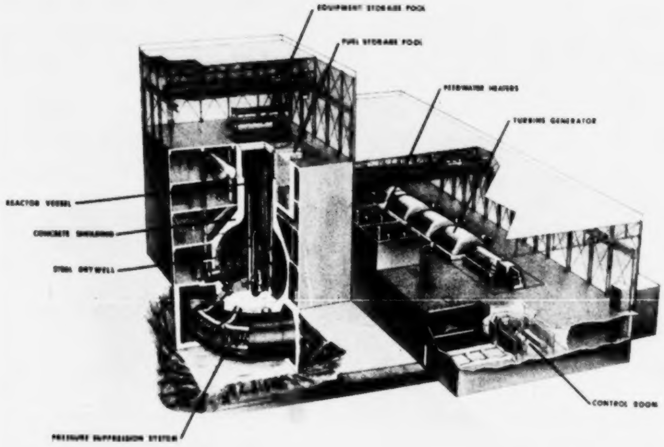
The second direction in which the use of nuclear energy has been pushed on a large scale has been in the production of electrical power from the energy released in fission. The increasing need for electrical energy is an important aspect of modern life. The amount of electricity used in an advanced industrial country, such as the United States, has been doubling approximately every ten years since about 1900. Although there are still large supplies of coal, oil and natural gas, it is evident that additional sources of energy will be needed, and nuclear energy from fission can fill this need.

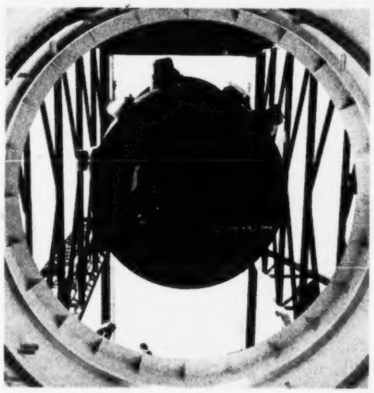
See "The Nuclear Energy Revolution" in Project Physics Reader 6.

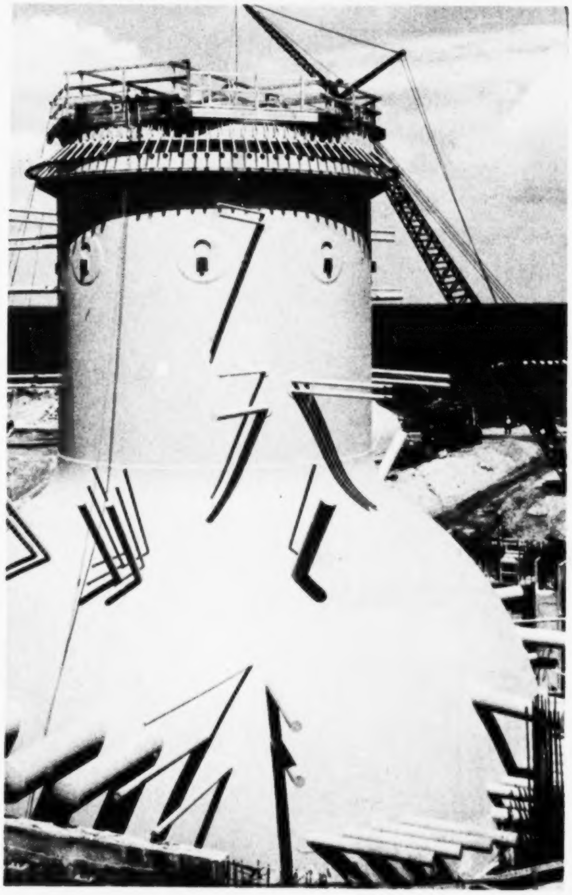
In almost all present systems of nuclear power production, the reactor is a source of heat for running steam turbines; the turbines drive electrical generators just as they do in conventional power stations.



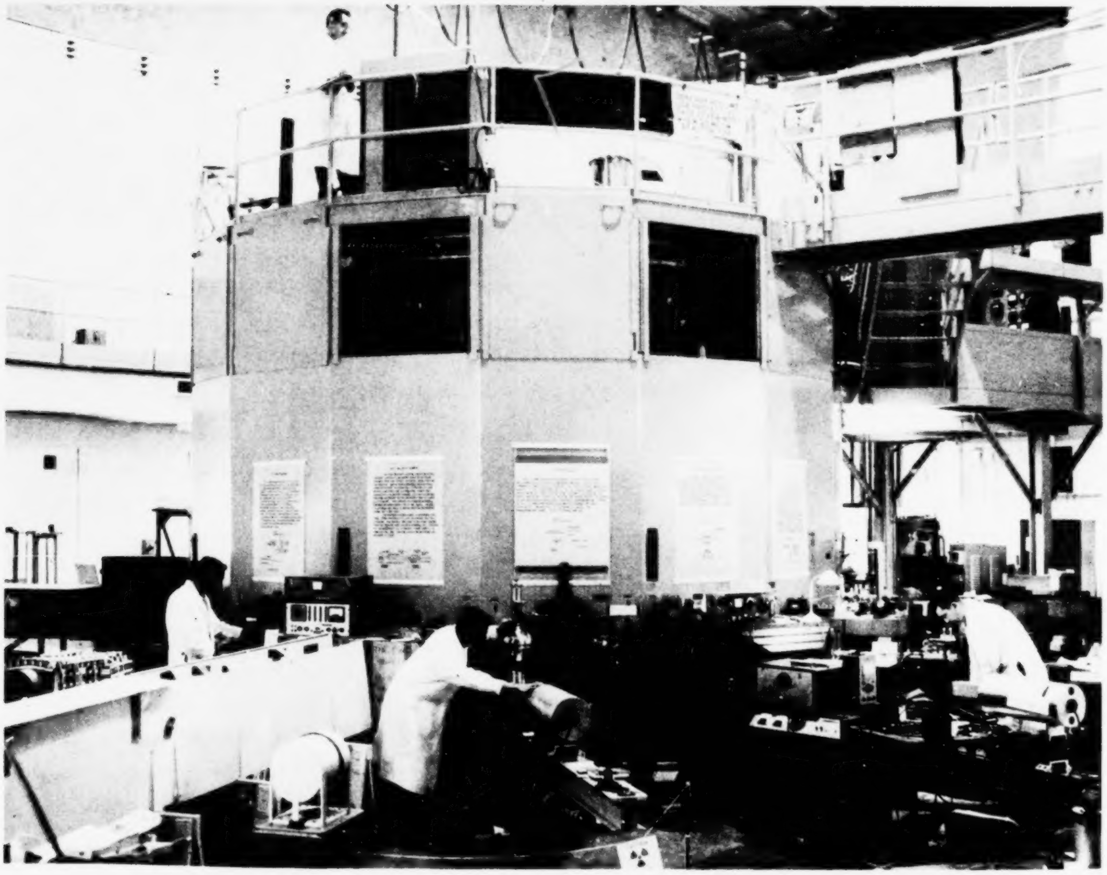


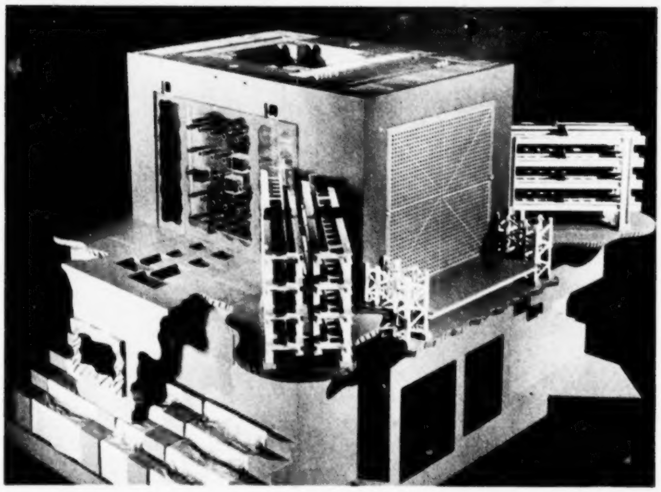

EQUIPMENT STORAGE POOL
FUEL STORAGE POOL
FEEDWATER HEATERS
TURBINE GENERATOR
REACTOR VESSEL
CONCRETE SHIELDING
STEEL DRYWELL
CONTROL ROOM
PRESSURE SUPPRESSION SYSTEM

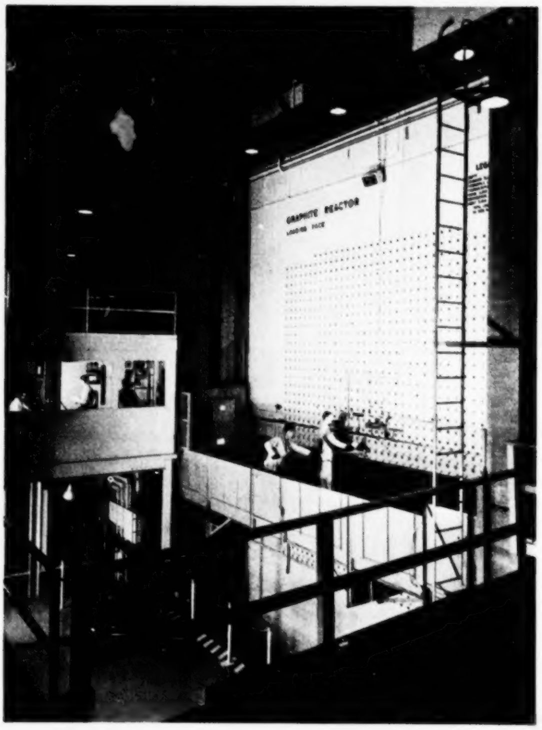




These photographs illustrate one type of commercial installation for converting the heat energy from a fusion chain reaction into electrical energy. The steel "drywell" at the left is the housing for the nuclear reactor at the Nine Mile Point generating station, near Oswego on Lake Ontario. Just above, the reactor vessel is shown being lowered into the drywell. A later stage of construction is shown at the top. The cutaway drawing shows the reactor, turbine-generator and other components of a similar installation: the Dresden nuclear power station at Joliet, Illinois.






GRAPHITE REACTOR
LOADING FACE

The photos on this page show 3 research reactors.

At the top is the small research reactor at M.I.T. in Cambridge, Mass.

At the right, technicians load fuel slugs in the A.E.C.'s graphite reactor at Oak Ridge, Tennessee.

Above is a model of the Brookhaven graphite reactor.

24.7

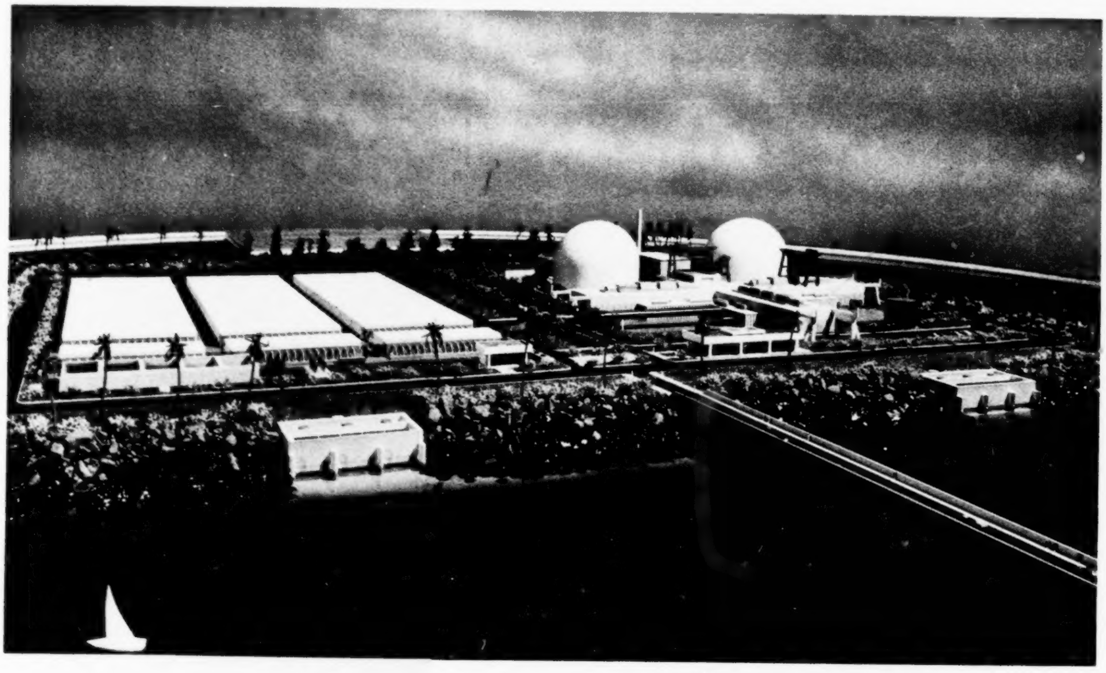
See "A Report to the Secretary of War," "Twentieth Birthday of the Atomic Age" and "Calling All Stars" in Project Physics Reader 6.

For a variety of reasons, some administrative and some technical, but mostly connected with the "Cold War" that started after World War II and intensified during the early fifties, the U. S. Atomic Energy Commission (AEC) did not emphasize applied research on nuclear-electric power systems until President Eisenhower so directed in 1953. By that time America's first experimental breeder reactor (EBR-1) had demonstrated for two years in Idaho that electric power could be produced in significant amounts while simultaneously producing plutonium from the U^{238} blanket around the neutron-and energy-producing core.

Not until fully twenty years after the Manhattan Project reached its goals could one say that the age of nuclear-electric generation of power had arrived. Nuclear energy sources became economically competitive with hydroelectric and fossil-fuel sources in the early 1960's when costs per kilowatt-hour were reduced to as low as one-half cent. In 1966 there were 29 contracts for construction of large nuclear power reactors in the United States alone. This commitment represented more than half of the total new power plant construction in the United States. The British and French also successfully used reactors to generate commercial electric power. Thus there finally are strong reasons for optimism concerning new sources of energy.

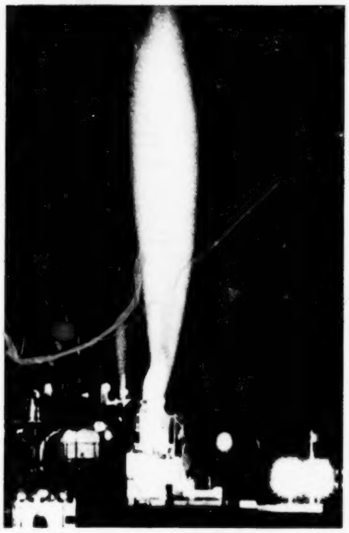
Below is shown a model of a nuclear power and desalting plant to be built on a man-made island off the coast of southern California. It will generate electricity at the rate of 1.8 million kilowatts and also produce, by distillation, 150 million gallons of fresh water daily.

Such new sources were clearly needed, for along with the population explosion, the depletion of fossil fuels and the falling water table, an energy shortage threatened

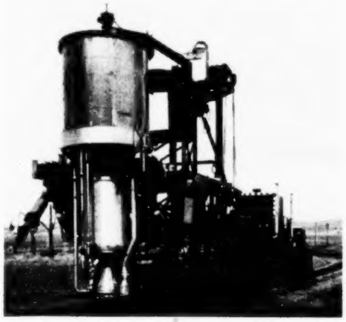


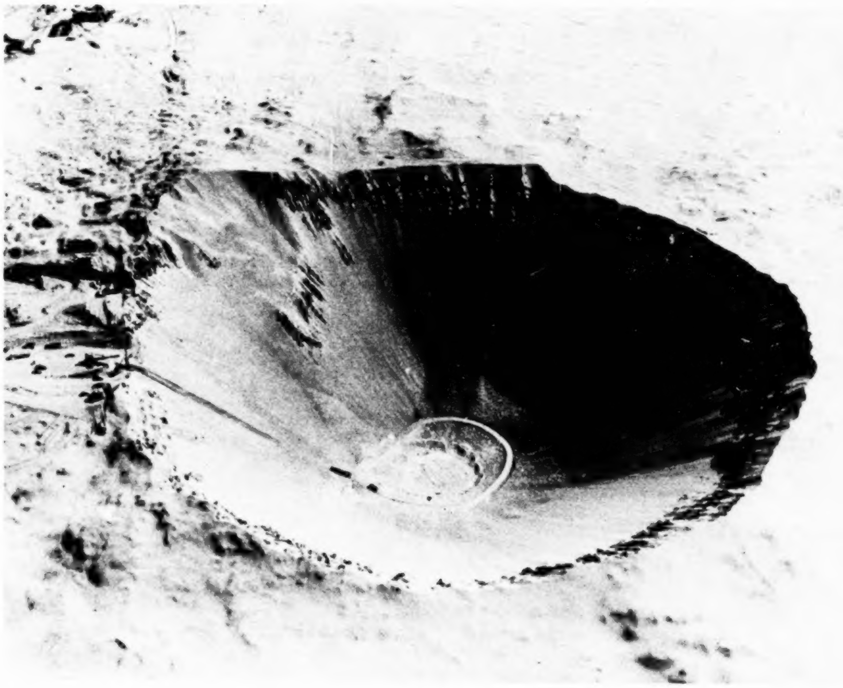
to limit mankind's future development. Power reactors, now entering a third generation of development, show definite promise of being able to desalt sea water economically, to convert atmospheric nitrogen into powdered fertilizers, and to make fluid fuels from hydrocarbons in low-grade coal. If all this can be done cheaply enough with breeder reactors that produce at least as much fissionable material as they "burn," then indeed the war-born nuclear technology at last can have the beneficial impact on all of human society that is so desperately needed.

In the meantime, the social costs of the nuclear energy revolution have already been very high—in human lives, in money, and in the anxiety of life under the threat of nuclear war. In some ways these are analogous problems to the human price of industrialization after the development of the steam engine (Unit 3). At the same time, the potential benefit to man is great. As in the past, the decisions that will be necessary in the future development of nuclear power cannot be made on the basis of physics alone. Science can illuminate alternatives, but it cannot and should not be used by itself to choose among them. Responsible scientific opinion must be supplemented by political insight and a broad humanistic view of society. But at the very least, responsible citizens must have some understanding of the scientific principles that will underlie the alternatives among which they must choose.



A blast of hydrogen exhaust (above) from an experimental nuclear rocket engine (below).





Among the many problems for public policy raised by developments in nuclear power is the Plowshare program of the A.E.C. The crater at the left was part of Plowshare's research into creating lakes, harbors and sea-level canals between oceans by the use of thermonuclear explosions.

Chronology of Developments in Nuclear Science and Technology

1896	Becquerel discovers unstable (radioactive) atoms.
1899	Isolation of radium by Curies.
1905	Einstein announces equivalence of mass and energy.
1911	Rutherford discovers nucleus.
1919	Rutherford achieves transmutation of one stable chemical element (nitrogen) into another (oxygen).
1920-1925	Improved mass spectrographs show that changes in mass per nuclear particle accompanying transmutation account for energy released by nucleus.
1931	Lawrence and Livingston construct first cyclotron.
1932	Chadwick identifies neutrons.
1939	Evidence of uranium fission by Hahn and Strassmann, identification of fission products by Meitner and Frisch.
1940	Discovery of neptunium and plutonium (transuranium elements) at the University of California.
1942	Achievement of first self-sustaining nuclear reaction, University of Chicago.
1945	First test of an atomic device, at Alamagordo, New Mexico, followed by the dropping of atomic bombs on Hiroshima and Nagasaki, at the end of World War II.
1946	President Truman signs the bill creating the U.S. Atomic Energy Commission.
	First shipment of radioactive isotopes from Oak Ridge goes to hospital in St. Louis, Missouri.
1951	First significant amount of electricity (100 kilowatts) produced from atomic energy at testing station in Idaho.
1952	First detonation of a hydrogen bomb, Eniwetok Atoll, Pacific Ocean.
1953	President Eisenhower announces U.S. Atoms-for-Peace program and proposes establishment of an international atomic energy agency.
1954	First nuclear-powered submarine, Nautilus, commissioned.
1955	First United Nations International Conference on Peaceful Uses of Atomic Energy held in Geneva, Switzerland.
1956	First commercial power plant begins operation at Calder Hall, England.
1957	Shippingport Atomic Power Plant in Pennsylvania reaches full power of 60,000 kilowatts.
	International Atomic Energy Agency formally established.
1959	First nuclear-powered merchant ship, the Savannah, launched at Camden, New Jersey.
1961	A radioactive isotope-powered electric generator placed in orbit, the first use of nuclear power in space.
1962	Nuclear power plant in the Antarctic becomes operational
1963	President Kennedy ratifies the Limited Test Ban Treaty for the United States.
1964	President Johnson signs law permitting private ownership of certain nuclear materials.
1966	Beginning of the rapid development of nuclear power plants in the U.S.
1968	"Non-proliferation" agreement, signed by the United States, the Soviet Union and other countries, limiting the number of countries possessing nuclear weapons.

24.8 Nuclear fusion. Fusion reactions have been produced in the laboratory by bombarding appropriate targets with, for example, high-energy deuterons from a particle accelerator. In these reactions energy is liberated, as expected. Some typical examples of fusion reactions, together with the energy liberated in each reaction, are:

$$_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + 4 \text{ MeV},$$

$$_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + {}_0n^1 + 3.3 \text{ MeV},$$

$$_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0n^1 + 17.6 \text{ MeV},$$

$$_1H^2 + {}_2He^3 \longrightarrow {}_2He^4 + {}_1H^1 + 18.3 \text{ MeV}.$$

In the first of the above equations, one product nucleus is an isotope of hydrogen, called tritium, with mass number $A = 3$; it is radioactive with a half-life of about 12 years and it decays by beta emission into $_2He^3$, an isotope of helium. When a target containing tritium is bombarded with deuterons, $_2He^4$ can be formed, as in the third equation above, liberating 17.6 MeV of energy. Of this energy, 14.1 MeV appears as kinetic energy of the neutron and 3.5 MeV as kinetic energy of the α particle.

Although the energy liberated in a single fusion is less than in a single fission, the energy per unit mass is much greater. About 50 helium atoms are needed to equal the mass of 1 uranium atom; 50 × 17.6 MeV is 1040 MeV—compared to 200 MeV for a typical fission.

The fusion of tritium and deuterium offers the possibility of providing large sources of energy, for example, in electric power plants. Deuterium occurs in water with an abundance of about one part in seven thousand of H^1 and can be separated from the lighter isotope. One gallon of water contains about one-eighth of a gram of deuterium which can be separated at a cost of about 4 cents. If this amount of deuterium could be made to react with tritium under appropriate conditions, the energy output would be equivalent to that from about 300 gallons of gasoline. The total amount of deuterium in the oceans is estimated to be about 10^{17} kilograms, and its energy content would be about 10^{20} kilowatt-years. If deuterium and tritium could be used to produce energy, they would provide an enormous source of energy. There are, however, some difficult problems to be solved, and some of these will be discussed briefly.

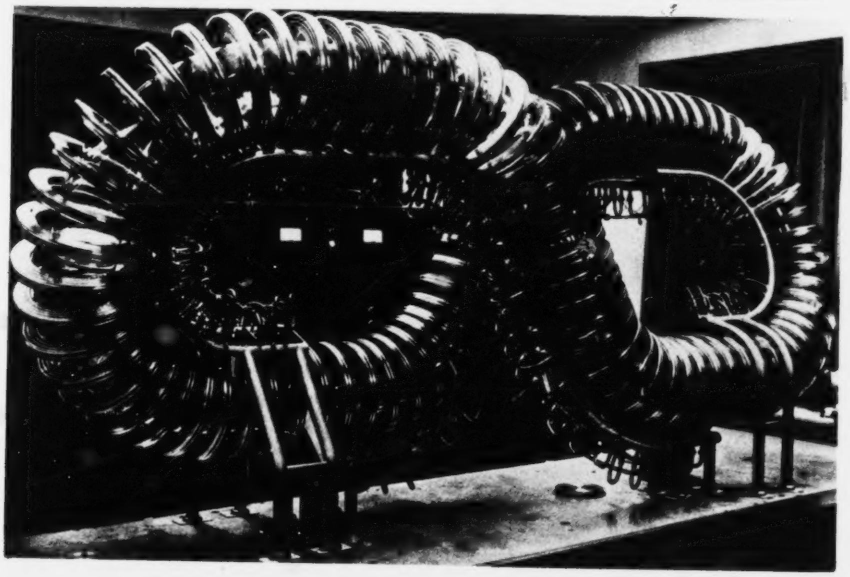
The nuclei which react in the fusion processes are positively charged and repel one another because of the repulsive electric force. The nuclei must, therefore, be made to collide with a high relative velocity to overcome the repulsive force tending to keep them apart. Experiments have shown that this can occur when the particles have kinetic energies of about 0.1 MeV or more. The nuclei must also be confined in a region where they can undergo many collisions without escaping, being absorbed by the walls bounding the region or losing energy by collisions with cooler molecules. There must be enough collisions per unit time so that fusion can occur at a rate that will yield more energy than that needed to cause the collisions. The combination of these requirements means that the nuclei must be contained at a temperature of the order of 100 million degrees.

Plasma: ionized gas in which positively and negatively charged particles move about freely.

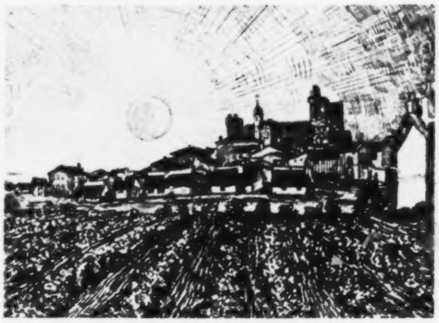
At the temperatures required for fusion, the atoms have been stripped of their electrons, and the resulting nuclei and separated electrons are said to form a plasma. No wall made of ordinary material can contain a hot plasma at 10^8°K (the wall would be vaporized instantly!). But the charged particles of a plasma could, in theory, be contained in an appropriately designed magnetic field. The first problem to be solved, therefore, is to contain the plasma of deuterium and tritium nuclei in a magnetic field, while accelerating the nuclei by means of an electric field to the required kinetic energy (or temperature). The rate at which the fusion reactions occur must also be regulated so as to produce energy which can be converted to electrical energy. These problems have not yet been solved on a practical scale, but research on them is being carried on in many countries. There is considerable international cooperation in this research, including visits of research teams between the United States, Britain and the U.S.S.R. Although the effort and expense are great, the possible pay-off in terms of future power resources is enormous.

Q9 Why are very high temperatures required to cause fusion reactions?

Q10 How could extremely hot gases be kept from contacting the wall of a container?



A demonstration model of a "Stellarator." The figure-eight shape enables strong magnetic fields to contain a continuous plasma stream in which a controlled fusion reaction might occur.



Pen drawing by Vincent van Gogh

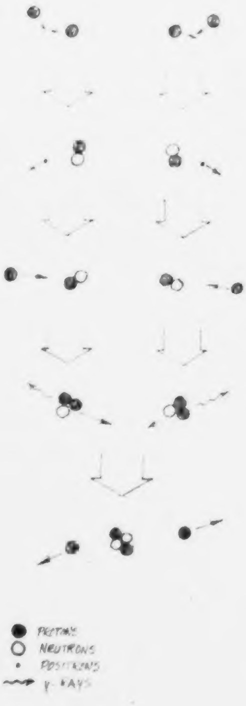
24.9 Fusion reactions in stars. One of the most fascinating aspects of nuclear physics is the study of the sources of the energy of different types of stars. Let us take the sun as an example. In the sun the fusion process involves the production of a helium nucleus from four protons. The net results of the reactions can be written as:

$$4\ {}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0 + 26\ \text{MeV}.$$

The reaction does not take place in a single step but can proceed through different paths of sets of reactions whose net results are summarized in the above equation; the amount of energy released is 26 MeV. The fusion of four protons into a helium nucleus is the main source of the energy of the sun. Chemical reactions cannot provide energy at large enough rates (or for long enough duration!) to account for energy production in the sun, but nuclear fusion reactions can. Hydrogen and helium together make up about 99 percent of the sun's mass, with approximately twice as much H as He, so there is plenty of hydrogen to supply the sun's energy for millions of years to come.

The possibility that four protons could collide to form a helium nucleus has been ruled out because the probability for such a reaction under solar conditions is too low to account for the amount of energy released. It now seems more likely that the four protons are formed into a helium nucleus in several steps, that is, by a series of nuclear reactions. We shall mention briefly one such series. When the temperature reaches about 10^7°K, the kinetic energies are large enough to overcome the electric repulsion between protons, and fusion of two protons (${}_1H^1$) takes place. The nuclear reaction results in a deuteron (${}_1H^2$), a positron (${}_{+1}e^0$) and a neutrino. As soon as a deuteron is formed, it reacts with another proton resulting in helium 3 (${}_2He^3$) and a γ ray. The helium 3 nuclei fuse with each other forming α particles and two protons. In each of these reactions energy is released, resulting in 26 MeV for the complete cycle of four protons forming a helium nucleus.

One form of proton-proton fusion chain which releases energy in stars:



The rates of the reaction depend on the number of nuclei per unit volume and on the temperature; the higher the temperature, the faster the thermal motion of the particles and the more frequent and energetic the collisions. At the temperature of the sun's interior, which has been estimated to be 10 to 20 million degrees, the kinetic energies resulting from the thermal motion are in the neighborhood of 1 KeV.

Man has been able to achieve the release of large amounts

See "Power from the Stars" in Project Physics Reader 6.

of energy by means of fusion processes in thermonuclear explosions, such as hydrogen bombs. A hydrogen bomb consists of a mixture of light elements with a fission bomb. The latter acts as a fuel that initiates the fusion of the light elements. The explosion of a fission bomb produces a temperature of about 5 × 10^{7}° K, which is sufficiently high to make fusion possible. The fusion reactions then release additional large amounts of energy. The total energy release is much greater than would be liberated by the fission bomb alone.

SG 24.11
SG 24.12
SG 24.13
SG 24.14
SG 24.15
SG 24.16

Q11 Is the ratio of the amount of hydrogen to the amount of helium in the sun increasing or decreasing?

24.10 The strength of nuclear forces. The large energies involved in nuclear reactions, a million or more times larger than the energies involved in chemical (molecular) reactions, indicate that the forces holding the nucleus together are very much stronger than the forces that hold molecules together. Another clue to the magnitude of nuclear forces is the density of a typical nucleus. The work of Rutherford and his colleagues on the scattering of α particles showed that atomic nuclei have radii in the neighborhood of 10^{-13} cm to 10^{-12} cm; this means that the volume of an atomic nucleus may be as small as 10^{-39} to 10^{-36} cm^3. Now, the mass of one of the lighter atoms is of the order of 10^{-24} gram, and this mass is almost all concentrated in the nucleus, with the result that the density of the nucleus may be as high as 10^{12} to 10^{14} grams per cubic centimeter. Densities of such magnitude are thousands of billions of times beyond the limits of our ordinary experience since the greatest densities of ordinary material are in the neighborhood of 20 grams per cubic centimeter (uranium, gold, lead). It is evident that the forces that hold the atomic nucleus together must be very different from any forces we have considered so far. The search for understanding of these forces is one of the most important problems of modern physics and one of the most difficult. Although a good deal has been learned about nuclear forces, the problem is far from solved.

Information about nuclear forces has been obtained in several ways. It is possible to deduce some of the properties of nuclear forces from the known properties of atomic nuclei, for example, from the binding energy curve of Fig. 24.1b. That curve shows that the average binding energy per particle in a nucleus has nearly the same value for all but the lightest nuclei—about 8 MeV. In other words, the total binding energy of a nucleus is nearly proportional to the number of particles in the nucleus. Now, if every particle in the nucleus were to interact with every other particle, the energy of the interactions and, therefore, the binding energy would be approximately proportional to the number of interacting pairs. Each of the particles would interact with all others. The binding energy calculated by assuming such interacting pairs is very different from the experimental results. To avoid this contradiction it is necessary to assume that a nuclear particle does not interact with all other nuclear particles but only with a limited number of them, that is, only with its nearest neighbors. For this to be the case the nuclear forces must have a short range. The nuclear forces must fall off very rapidly as the distance between two nucleons increases. This decrease must be more rapid than the $1/r^2$ decrease of the gravitational force between two particles or the $1/r^2$ decrease of the Coulomb electric force between two charges.

The presence of protons in the nucleus also tells us something about nuclear forces. Since there are only positively charged and neutral particles in the nucleus, the electric forces must be repulsive. Since the nucleus is very small—of the order of 10^{-12} cm in diameter—these forces must be enormous. So why is the nucleus stable? It seems reasonable to assume that the electric repulsion is overcome at very small distances by very strong attractive forces between the nuclear particles. Information about such specifically nuclear forces can be obtained by studying the scattering of protons or neutrons by materials containing protons. Scattering experiments and the theory needed to account for their results form an important branch of nuclear physics. They show that such attractive nuclear forces do indeed exist, and many of the properties of these forces are now known—but not all. The complete solution of the problem of nuclear forces and how they hold the nucleus together has not yet been obtained; this problem lies at the frontier of nuclear research.

In the absence of a complete theory of nuclear forces and structure, models of the nucleus have been developed. Several models are used because no one model adequately describes the wide variety of nuclear phenomena, ranging from particle emission in radioactive decay to nuclear reactions and fission. Two of these models are of special interest: the liquid drop model and the shell model.

Q12 **Why was it assumed that there are special nuclear forces to hold the nucleus together?**

Q13 **Why was it assumed that the nuclear force is very short-range?**

See "Models of the Nucleus" in Project Physics Reader 6.

24.11 The liquid-drop nuclear model. In the liquid drop model the nucleus is regarded as analogous to a charged drop of liquid. This model was suggested because the molecules in a liquid drop are held together by short-range forces, as are the nucleons in a nucleus. According to this model, the particles in the nucleus, like the molecules in a drop of liquid, are in continual random motion. In analogy with the evaporation of molecules from the surface of a liquid drop, a group of nuclear particles may pick up enough energy through chance collisions with other nucleons to overcome the attractive nuclear forces and escape from the nucleus; this process would correspond to spontaneous α emissions. This model has been especially useful in describing nuclear reactions: a particle may enter the nucleus from outside and impart enough additional kinetic energy to the protons and neutrons to permit the escape of a proton or a neutron, or a combination such as a deuteron or an α particle. A quantitative theory of nuclear reactions based on this idea has been developed.

The usefulness of the liquid drop model is also shown in its ability to account for fission. When a sample of U^{235} is bombarded with slow neutrons, that is, neutrons whose kinetic energy is very small, a U^{235} nucleus may capture a neutron to form a U^{236} nucleus. We can calculate the binding energy of the captured neutron:

mass of U^{235} nucleus = 235.04393 amu
mass of neutron = 1.00867
total mass of the separate parts = 236.05260
mass of U^{236} nucleus = 236.04573
change of mass (Δm) = 0.00687 amu
binding energy = $0.00687 \text{ amu} \times 931 \frac{\text{MeV}}{\text{amu}}$
= 6.4 MeV.

At that instant when the neutron is captured, the U^{236} nucleus formed has this additional energy, 6.4 MeV, which is called the "excitation energy due to the neutron capture." This energy is several MeV even though the kinetic energy of the neutron is so small, less than 1 eV, that it can be neglected.

What happens to the excited U^{236} nucleus? This problem was studied theoretically in 1939 by Niels Bohr, who had come to the U. S., and John A. Wheeler, an American physicist. They showed that, according to the liquid drop model, the U^{236} can act like a drop of mercury when "excited" by being given mechanical energy. The nucleus can be deformed into an elongated or dumbbell-like shape whose two (charged) parts may be beyond the range of the attractive nuclear forces. The electric force of repulsion between the two parts of the deformed nucleus can overcome the short-range attractive forces, causing the nucleus to split, that is to undergo fission, and causing the fragments to separate with high velocity. Each of the fragments will then quickly assume a spherical (or nearly spherical) form because within it the attractive nuclear forces again predominate. A schematic picture of a possible sequence of steps is shown in Fig. 24.3. Fission occurs less than one billionth (10^{-9}) of a second after the neutron is captured.

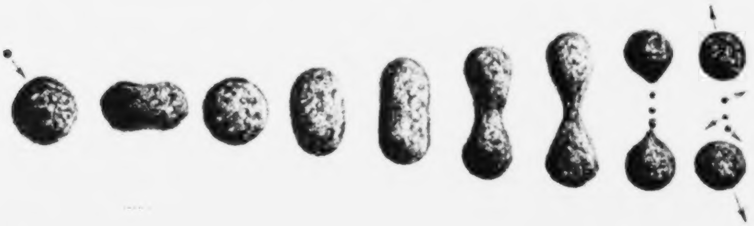


Fig. 24.3 Schematic representation of steps leading to the fission of a compound nucleus, according to the liquid drop model.

The liquid drop model gives a simple answer to the question: why do some nuclides (U^{235} and Pu^{239}) undergo fission with slow neutrons while others (Th^{232} and U^{238}) undergo fission only with fast neutrons? The answer is that a certain minimum amount of energy must be supplied to a nucleus to deform it enough so that the repulsive electric forces can overcome the attractive nuclear forces. This energy, called the activation energy, can be calculated with the aid of the mathematical theory of the liquid drop model. When U^{235} captures a neutron to make U^{236}, the excitation of the U^{236} nucleus is greater than the energy required for fission, even when the neutron has very low kinetic energy. This calculation was made by Bohr and Wheeler in 1939; they predicted, correctly, that U^{235} would undergo fission with slow neutrons. The theory also predicted that when U^{238} captures a slow neutron to form U^{239} the excitation energy is smaller than the activation energy by 0.9 MeV. Hence U^{238} should undergo fission only when bombarded with neutrons with kinetic energies of 0.9 MeV or more. The correctness of this prediction was verified by experiment.

When U^{235} captures a neutron to make U^{236}, the excitation of the U^{236} nucleus is greater than the energy required for fission, even when the neutron has very low kinetic energy.

SG 24.17

SG 24.18

Q14 According to the liquid drop model, what kind of force causes fission?

Q15 Why does U^{238} require fast neutrons to provoke fission?

24.12 The shell model. Another nuclear model is required to account for other properties of the nucleus—properties that could not be accounted for by the liquid drop model. We saw in Sec. 22.7 that nuclides with even numbers of neutrons and protons are more stable than nuclides that contain odd numbers of either protons or neutrons. Detailed experimental studies of nuclear stability have shown that nuclei having 2, 8, 20, 50 or 82 protons, or 2, 8, 20, 50, 82 or 126 neutrons are unusually numerous and stable. These nuclei have greater binding energies than closely similar nuclei. When the exceptional properties of nuclei with these numbers of protons and neutrons became clear, in 1948, no available theory or model of the nucleus could account for this situation. The numbers 2, 8, 20, 50, 82 and 126 were referred to as "magic numbers."

It was known from the study of atomic properties that atoms with atomic numbers 2, 10, 18, 36, 54 and 86—the noble or inert gases helium to radon—also have special stability properties. These properties were explained in the Bohr-Rutherford model of the atom by the idea that the electrons around each nucleus tend to arrange themselves in concentric shells, with each shell able to contain only a certain maximum number of electrons: 2 for the innermost shell, 8 for the next, and so on. A full electron shell corresponds to an especially stable atom. Although the Bohr-Rutherford model has been replaced by quantum mechanics, the idea of shells still provides a useful picture, and a nuclear model—the nuclear shell model—has been developed.

As with the electron, the "shells" are thought of as quantized energy states.

In the nuclear shell model it is assumed that protons can, in a rough way of speaking, arrange themselves in shells, and that neutrons can, independently, do likewise; in the magic-number nuclei the shells are filled. The model has been worked out in great detail on the basis of quantum mechanics, and has been successful in correlating the properties of nuclides that emit α or β particles and γ photons, and in describing the electric and magnetic fields around nuclei. But the nuclear shell model does not help us understand fission, and there are fundamental differences between this model and the liquid-drop model. For example, the shell model emphasizes definite patterns in which nucleons are arranged, while the liquid-drop model pictures the nuclear material in random motion. Each model is successful in accounting for some nuclear phenomena but fails for others.

When two seemingly contradictory theories or models must be used in a field of physics, a strong effort is put into trying to develop a more general viewpoint, or theory, which can include the two as special cases. Such a nuclear theory is being developed; it is called the collective model, and one of the physicists who has worked on this model is Aage Bohr, the son of Niels Bohr. This model represents an advance beyond the shell and liquid-drop models in correlating nuclear data. It does not answer the fundamental question of the nature of nuclear forces, which is still one of the chief problems in the physics of our times.

Q16 According to the shell model, what makes the "magic numbers" of protons and neutrons magic?

Q17 Which is better, the liquid drop or the shell model?

24.13 Biological and medical applications of nuclear physics. In Sec. 24.7 we mentioned the military applications of nuclear energy and the use of nuclear energy as a source of electric power. There are many other applications which may, in the long run, turn out to be more important. These may be included under the general heading of radiation biology and medicine. The field of science indicated by this name is broad and we can only indicate, by means of a few examples, some of the problems that are being worked on. In this work, radiations are used in the study of biological phenomena, in the diagnosis and treatment of disease, and in the improvement of agriculture.

The physical and chemical effects of various kinds of radiations on biological materials are being studied to find out, for example, how radiation produces genetic changes. The metabolism of plants and animals is being studied with the aid of extremely small amounts of radioactive nuclides called isotopic tracers, or "tagged atoms." A radioactive isotope (for example, C^{14}) acts chemically and physiologically like a stable isotope (C^{12}). Hence a radioactive tracer can be followed with counters as they go through various metabolic processes. The ways in which these processes take place can be studied accurately and relatively easily by means of these techniques. The role of micronutrients (elements that are essential, in extremely small amounts, for the well-being of plants and animals) can be studied in this way. Agricultural experiments with fertilizers containing radioactive isotopes have shown at what point in the growth of a plant the fertilizer is essential. In chemistry, radioactive isotopes help in the determination of the details of chemical reactions and of the structure of complex molecules, such as proteins, vitamins and enzymes.

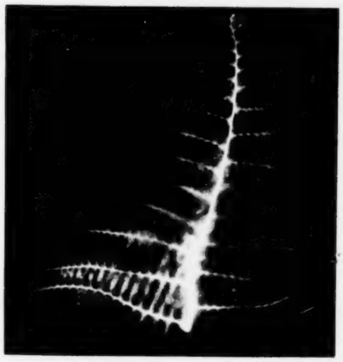
Table 24.1

Isotope	Half-life	Important Uses
$_1H^3$	11 years	Used as a tag in organic substances.
$_6C^{14}$	4700 years	Used as a tag in studying the synthesis of many organic substances. When $_6C^{14}$ is incorporated in food material, the metabolic products of the organism are marked with it.
$_{11}Na^{24}$	15 hours	Useful in a wide variety of biochemical investigations because of its solubility and chemical properties.
$_{15}P^{32}$	14 days	For the study of bone metabolism, the treatment of blood diseases and the specific uptake in tumor tissue.
$_{16}S^{35}$	87 days	Has numerous chemical and industrial applications.
$_{27}Co^{60}$	5.3 years	Because of its intense γ emission, may be used as a low-cost substitute for radium in radiography and therapy.
$_{53}I^{131}$	8 days	For the study of thyroid metabolism and the treatment of thyroid diseases.

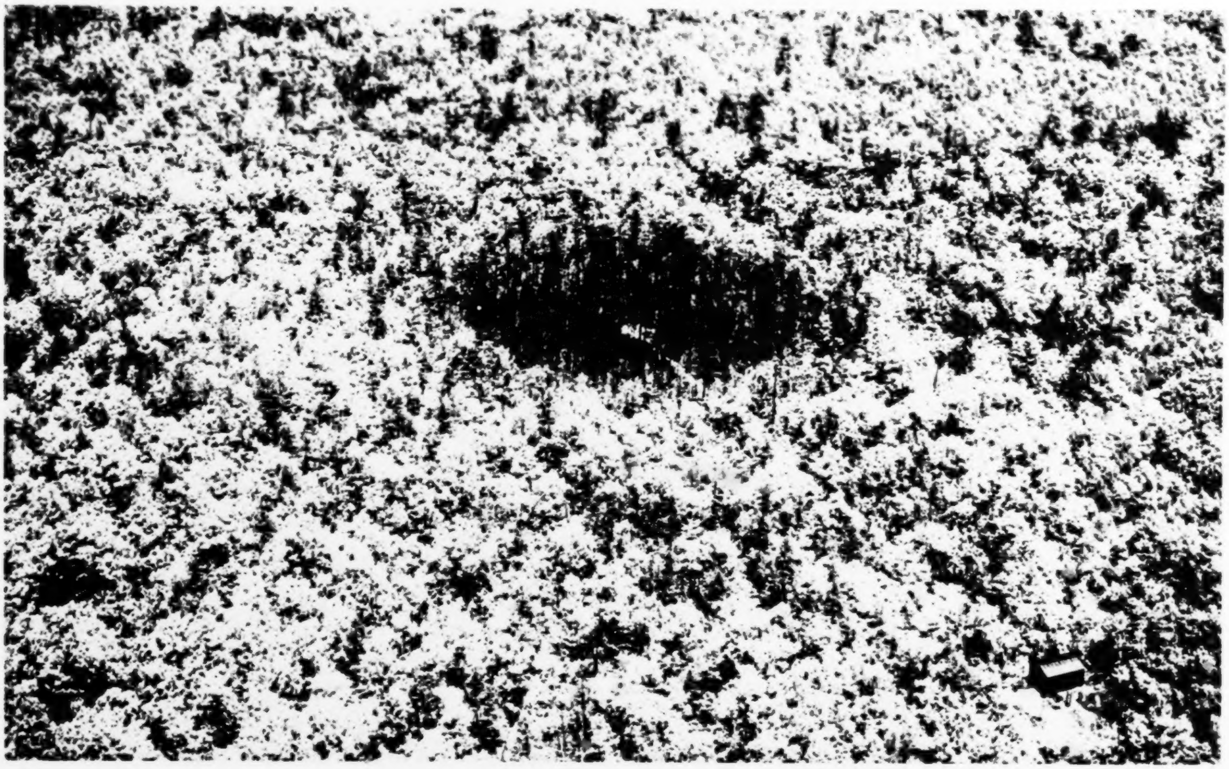
Perhaps the most rewarding uses of radioisotopes have been in medical research, diagnosis and therapy. For example, tracers can help to determine the rate of flow of blood through the heart and to the limbs, thus aiding in the diagnosis of abnormal conditions. Intense doses of radiation can do serious damage to living cells. Diseased cells are often more easily damaged than normal cells. Radiation can, therefore, be used to treat some diseases, such as cancer. Some parts of the body take up particular elements preferentially. For example, the thyroid gland absorbs iodine easily. Specially prepared radioisotopes of such elements can be administered to the victims of certain diseases, thus supplying desired radioactivities right at the site of the disease. This method has been used in the treatment of cancer of the thyroid gland, blood diseases and brain tumors and in the diagnosis of thyroid, liver and kidney ailments.

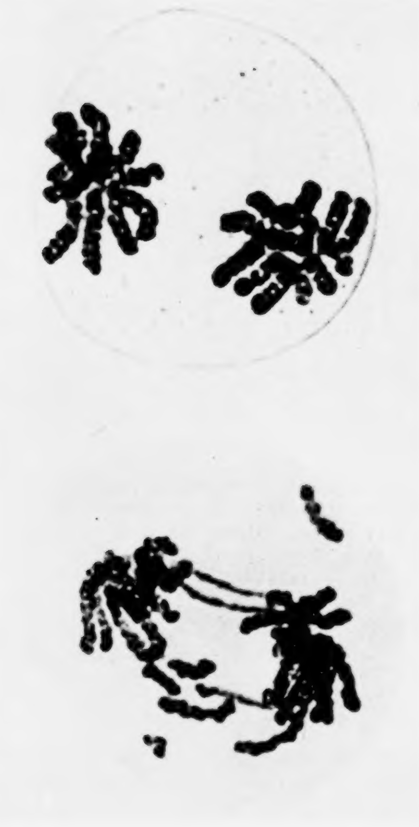
Table 24.1 summarizes the use of a few radioisotopes, most of which are produced by neutron bombardment in nuclear reactors. Such uses suggest the promise that nuclear physics holds for the future. Indeed, they symbolize the meaning of science at its best: research in science lays open to our understanding the secrets of nature—and from the application of this knowledge to human needs, all mankind can benefit.

A grain of radioactive dust in the atmosphere is the origin of these α-particle tracks in a photographic emulsion (enlarged 2000 times).



An autoradiograph of a fern frond made after the plant had taken in a solution containing radioactive sulfur 35.





At the top, the damaged trees surround a radioactive cesium 137 capsule which had been kept there for nearly 6 months in an experiment to study the effects of ionizing radiation on biological systems.

The upper portion of the photo at the left shows normal plant cell chromosomes divided into 2 groups. Below that the same cell is shown after x-ray exposure. Fragments and bridges between groups are typical radiation-induced abnormalities.

Above is a 14,000 yr. old burial site being uncovered by an archeological team near the Aswan Reservoir. The age of the burial site is determined by carbon-14 dating (described in SG 22.9) of scraps of wood or charcoal found in it.

24.1 Suppose that $_6C^{13}$ is formed by adding a neutron of a $_6C^{12}$ atom. Calculate the binding energy due to that neutron in C^{13}; the atomic masses of C^{12} and C^{13} are 12.000000 and 13.003354 amu.

24.2 The atomic mass of He^4 is 4.00260 amu; what is the average binding energy per particle?

24.3 Suppose that a proton with negligible kinetic energy induces the following reaction:

$$_3Li^7 + {_1H^1} \longrightarrow {_2He^4} + {_2He^4}.$$

If the lithium nucleus were initially at rest, what would be the relative directions of the two α particles? What would be the kinetic energy of each α particle?

24.4 The first nuclear transmutation (produced by Rutherford in 1919) was the reaction:

$$_7N^{14} + {_2He^4} \longrightarrow {_8O^{17}} + {_1H^1}.$$

The atomic masses involved are:

N^{14}: 14.003074 amu
O^{17}: 16.999134 amu
$_2He^4$: 4.002604 amu
$_1H^1$: 1.007825 amu

Is energy absorbed or released in this reaction? How much energy (in MeV) is involved?

24.5 In an experiment on the reaction of SG 24.4, the α particles used had a kinetic energy of 7.68 MeV, and the energy of the protons was 5.93 MeV. What was the "recoil" energy of the O^{17} nucleus?

24.6 Calculate the amount of energy (in MeV) liberated in the following nuclear reaction:

$$_7N^{14} + {_1H^2} \longrightarrow {_7N^{15}} + {_1H^1}.$$

The atomic masses are:

N^{14}: 14.003074
H^2 : 2.014102
N^{15}: 15.000108
H^1 : 1.007825

24.7 Appreciable amounts of the uranium isotope $_{92}U^{233}$ do not occur outside the laboratory. $_{92}U^{233}$ is formed after the thorium nucleus $_{90}Th^{232}$ has captured a neutron. Give the probable steps leading from $_{90}Th^{232}$ to $_{92}U^{233}$.

24.8 Use Fig. 24.1a to find the binding energies for U^{235}, Ba^{141} and Kr^{92}. Use these values to show that the energy released in the fission of U^{235} is approximately 200 MeV.

24.9 Possible end-products of U^{235} fission, when provoked by capture of slow neutrons, are $_{57}La^{139}$ and $_{42}Mo^{95}$. This reaction may be described by the equation:

$$_{92}U^{235} + {_0n^1} \longrightarrow {_{57}La^{139}} + {_{42}Mo^{95}} + 2\,{_0n^1} + 7({_{-1}e^0}).$$

The mass of $_{57}La^{139}$ is 138.8061 amu; that of $_{42}Mo^{95}$ is 94.9057 amu. How much energy is released per atom in this particular fission? The mass of the seven electrons may be neglected.

24.10 Loss of neutrons from a mass of fissionable material depends on its shape as well as its size. For some shapes, it is impossible to reach a critical size because the neutron loss through the surface is too great. With what shape would a mass of fissionable material suffer the least loss of neutrons from the surface? The most?

24.11 Why are the high temperatures produced by the explosion of a fission bomb necessary to initiate fusion in a thermonuclear device?

24.12 It is generally agreed that stars are formed when vast clouds of hydrogen gas collapse under the mutual gravitational attraction of their particles. How do fusion reactions begin in such stars?

24.13 One of the energy sources in the sun is the production of helium nuclei by four protons as described in Sec. 24.9: $4\,{}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0$. Show that about 26 MeV of energy are released in each cycle.

24.14 Fusion reactions in the sun convert a vast amount of hydrogen into radiant energy each second.

(a) Knowing that the energy output of the sun is 3.90×10^{26} joules/sec, calculate the rate at which the sun is losing mass.

(b) Convert the value 3.90×10^{26} joules/sec to horsepower. (Recall that 1 horsepower is equivalent to 746 watts).

24.15 A source of energy in the sun may be the "carbon cycle," proposed by Hans Bethe, which is outlined below. Complete the six steps of the cycle.

$${}_6C^{12} + {}_1H^1 \longrightarrow \underline{\qquad} + \gamma$$

$$\underline{\qquad} \longrightarrow {}_6C^{13} + {}_{+1}e^0 + \nu$$

$${}_6C^{13} + {}_1H^1 \longrightarrow \underline{\qquad} + \gamma$$

$$\underline{\qquad} + {}_1H^1 \longrightarrow {}_8O^{15} + \gamma$$

$${}_8O^{15} \longrightarrow \underline{\qquad} + {}_{+1}e^0 + \nu$$

$$\underline{\qquad} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4$$

24.16 Another reaction which may take place in the sun is:

$$He^3 + He^4 \longrightarrow Be^7 + \gamma .$$

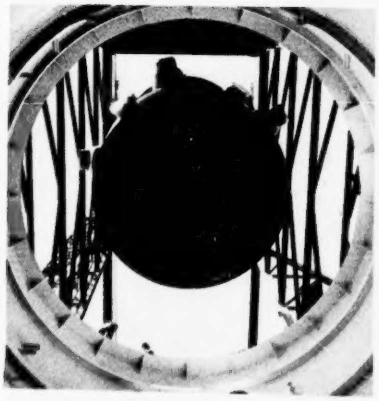
The atomic mass of He^3 is 3.016030 amu, and that of Be^7 is 7.016929. Is energy absorbed or released? How much energy?

24.17 The atomic masses of ${}_{92}U^{233}$ and ${}_{92}U^{234}$ are 233.039498 and 234.040900 amu. The activation energy for the fission of the nucleus ${}_{92}U^{234}$ is 4.6 MeV. Is U^{233} fissionable by slow neutrons?

24.18 Bombardment of ${}_{94}Pu^{241}$ with slow neutrons sometimes leads to the reaction:

$${}_{94}Pu^{241} + {}_0n^1 \longrightarrow {}_{94}Pu^{242} + \gamma .$$

The atomic masses of Pu^{241} and Pu^{242} are 241.056711 amu and 242.058710 amu. The activation energy of Pu^{241} is 5.0 MeV. Is Pu^{241} fissionable with slow neutrons?



Epilogue In this unit we have traced the development of nuclear physics from the discovery of radioactivity to current work in nuclear fission and fusion. We have seen how radioactivity provided a place to start from and tools to work with. In radioactivity man found the naturally occurring transmutation of elements that made it possible for him to achieve the transmutations sought by the alchemists. The naturally occurring radioactive series pointed to the existence of isotopes, both radioactive and stable. Artificial transmutation has increased by many hundreds the number of atomic species available for study and use.

Nuclear physicists and chemists study the reactions of the stable and radioactive nuclides; and so nuclide charts and tables grow. The collection and correlation of a vast body of experimental data remind us of the work of the nineteenth-century chemists and spectroscopists. Nuclear models are built, changed and replaced by newer and, perhaps, better models. But the detailed nature of nuclear forces is still the subject of much research, especially in the field of high-energy physics.

But that is only one of the fields that remains to be explored. The nucleus also has magnetic properties which affect the behavior of atoms. Sometimes it helps to study these properties when the atoms of matter are at very low temperatures, as close to absolute zero as we can get them. Nuclear physics overlaps with solid-state physics and with low-temperature physics; strange and wonderful things happen—and quanta again help us understand them.

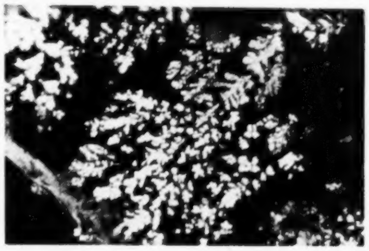
The study of light through the development of devices such as the laser attracts many physicists. These devices are made possible by, and contribute to, our increasing understanding of how electrons in complex atomic systems jump from one energy state to another—and how they can be made to jump where and when we want them to.

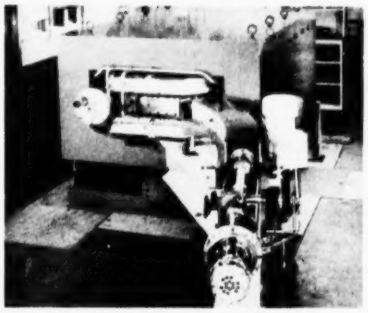
The properties of liquids are still only imperfectly understood after much study. Thales of Miletus was perhaps the first man on record to make a large-scale scientific speculation when he proposed, over twenty-six centuries ago, that maybe everything in the world is basically made of water in combinations of its various states. Thales was wrong, but even today we are trying to develop an adequate theory of the behavior of water molecules.

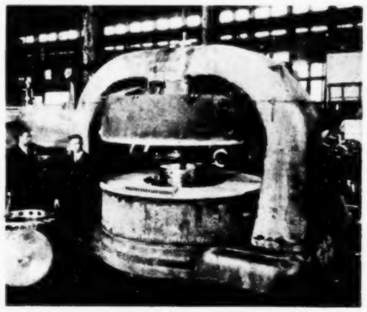
All the subjects we have mentioned touch on engineering, where physics and other disciplines are made to work for us. All of the engineering fields involve physics. Nuclear engineering and space engineering are the most recent and, at the moment, perhaps the most glamorous. But today the chemical engineer, the mechanical engineer and the metallurgist all use quantum mechanics. They must understand the properties of atoms and atomic nuclei, because it is no longer enough to know only the properties of matter in bulk.

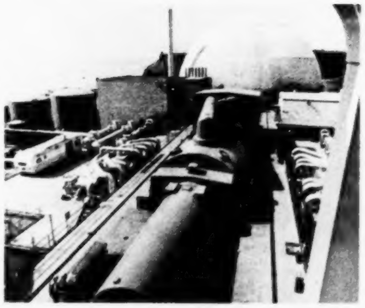
The radiations we have talked about—α, β and γ rays—are tools for industry, biology and medicine. They help to cure, preserve, study, understand. Neutrons are not only constituents of the nucleus, they are also probes for studies in science and in industry.

So our study of atoms and nuclei, indeed our whole course, has been an introduction not only to physics but also to the many fields with which physics is closely linked. It has been an introduction to an ever-expanding world in which much is known and understood, but where much more—and perhaps the most wonderful part—is waiting to be discovered.









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Brief Answers to Study Guide

Chapter 21

21.1 (a) The radioactivity of thorium was proportional to the amount of thorium.
(b) new radioactive elements polonium and radium

21.2 (a) 1.2×10^{-13} joule
(b) 0.75 MeV

21.3 (a) 5.7×10^{-2} m
(b) 420 m
(c) 7350:1

21.4 (a) 1.0×10^{4} N/coul
(b) 1.0×10^{3} volts
(c) undeflected

21.5 (a) γ (f) α
(b) α (g) β
(c) α (h) α
(d) γ (i) α
(e) γ (j) β

21.6 (a) Radium decayed into radon (a gas) which decays into radium A which is deposited on nearby objects.
(b) The residue contained daughters of high activity (short half-life).
(c) The uranium compound continually decayed into more active daughters, but daughters in the residue were not replaced as they decayed.

21.7 (a) 1/2
(b) 3/4
(c) Assume the products of decay were not themselves radioactive.

21.8 (a) graph
(b) 8.31×10^{19} atoms
(c) 5.0×10^{20} atoms

21.9 (a) 5.7×10^{-13} joules/disintegration
(b) 45 watts

21.10 3.70×10^{5} disintegrations/sec

21.11 5.0×10^{-3}/min
5×10^{3} atoms/min
Yes

21.12 10% of the 90% or 9% of the original.

Chapter 22

22.1 Isotopes of an element have same Z.

22.2 Determine if its chemical properties are unique.

22.3 (a) The lighter particles would diffuse away from the liquid surface more rapidly after evaporation, hence fewer of them would re-enter the liquid.
(b) The hydrogen isotopes have the largest ratio of isotopic masses (2:1) and hence the largest ratio of speeds ($1:\sqrt{2}$).

22.4 (a) 0.054 m
(b) 5.64 m
(c) 0.005 m

22.5 (a) $_{82}Pb^{212}$ $_{83}Bi^{212} + {}_{-1}e^{0}$
(b) $_{83}Bi^{212}$ $_{84}Po^{212} + {}_{-1}e^{0}$
(c) $_{84}Po^{212}$ $_{82}Pb^{201} + {}_{2}He^{4}$

22.6 chart, the end product being $_{82}Pb^{207}$.

22.7 diagram, ending with $_{82}Pb^{208}$. The alternatives are in the mode of decay of $_{84}Po^{216}$ and $_{83}Bi^{216}$.

22.8 decay diagram, the modes of decay are β, α, α, β, α, α.

22.9 4000 years
25000 years

22.10 (a) 12.011 amu
(b) 6.941 amu
(c) 207.2 amu

22.11 4.0015 amu

Chapter 23

23.1 235 is not divisible by 4.

23.2 235 protons
143 electrons

23.3 (a) $_{6}C^{13}$ (b) $_{12}Mg^{26}$ (c) $_{14}Si^{30}$
(d) $_{16}S^{32}$ (e) $_{19}K^{37}$

23.4 (a) $_{2}He^{3}$ (b) $_{3}Li^{6}$
(c) $_{4}Be^{8}$ (d) $_{0}n^{1}$

23.5 (a) γ (b) Al^{28}
(c) Mg^{24} (d) Mg^{25}
The same nuclide bombarded by different particles will yield different products.

23.6 Nitrogen nuclei are an order of magnitude more massive than hydrogen.

23.7 1.24 amu
6.9%

23.8 table

23.9 (a) 78 (b) 79 (c) 80

23.10 The missing product nuclide in each case is the same. $_{11}Na^{24}$.

23.11 description

23.12 explanation

23.13 explanation

Chapter 24

24.1 4.95 MeV

24.2 7.07 MeV/nucleon

24.3 opposite directions,
each with KE of 8.65 MeV

24.4 absorbed,
1.19 MeV

24.5 0.56 MeV

24.6 8.61 MeV

24.7 neutron capture,
β-decay
β-decay

24.8 U^{235}: 1790 MeV
Ba^{141}: 1180 MeV
Kr^{92}: 800 MeV

24.9 208 MeV

24.10 least loss—spherical
most loss—flat sheet

24.11 very high KE protons required

24.12 high enough temperatures result from the collapse

24.13 "proof"

24.14 (a) 4.33×10^{9} kg/sec
(b) 5.23×10^{23} horsepower

24.15 (1) $_{7}N^{13}$ (4) $_{7}N^{14}$
(2) $_{7}N^{13}$ (5) $_{7}N^{15}$
(3) $_{7}N^{14}$ (6) $_{7}N^{15}$

24.16 released
1.59 MeV

24.17 Yes, because the excitation energy is greater than the activation energy.

24.18 Yes

Appendix A Some Physical Constants and Conversion Factors

Name	Value
Speed of light	3.00×10^{8} m/sec
Planck's constant	6.63×10^{-34} J·sec
Charge of electron	-1.60×10^{-19} coul
Rest mass of electron	9.11×10^{-31} kg = 0.000549 amu
Rest mass of proton	1.67×10^{-27} kg = 1.007276 amu
Rest mass of neutron	1.67×10^{-27} kg = 1.008665 amu
Mass of neutral hydrogen atom	1.67×10^{-27} kg = 1.007825 amu

1 eV = 1.60×10^{-13} J

1 MeV = 10^{6} eV

1 amu = 931 MeV

Appendix B Some "Elementary" Particles

Family name	Particle name	Symbol	Rest mass*	Electric charge	Antiparticle	Average lifetime (seconds)
Photon	photon	γ (gamma ray)	0	neutral	same particle	infinite
Leptons	neutrino	ν, ν_μ	0	neutral	$\bar{\nu}$, $\bar{\nu}_\mu$	infinite
	electron	e^-	1	netative	e^+ (positron)	infinite
	μ-meson (muon)	μ^-	207	negative	μ^+	10^{-6}
Mesons	π-mesons (pions)	π^+	273	positive	π^- same as	10^{-8}
		π^-	273	negative	π^+ the	10^{-8}
		π°	264	neutral	π° particles	10^{-16}
	K-mesons (Kaons)	K^+	966	positive	K^- (negative)	
		K°	974	neutral	$\bar{K}^\circ$	10^{-10} and 10^{-7}
	η-meson (eta)	η°	1073	neutral	$\bar{\eta}^\circ$	10^{-18}
Baryons	proton	p	1836	positive	$\bar{p}$ (antiproton)	infinite
	neutron	n	1839	neutral	n (antineutron)	10^{3}
	lambda	Λ°	2182	neutral	$\bar{\Lambda}^\circ$	10^{-10}
	sigma	Σ^+	2328	positive	$\bar{\Sigma}^-$ (negative)	10^{-10}
		Σ^-	2341	negative	$\bar{\Sigma}^+$ (positive)	10^{-10}
		Σ°	2332	neutral	$\bar{\Sigma}^\circ$	10^{-20}
	xi	Ξ^-	2580	negative	$\bar{\Xi}^+$ (positive)	10^{-10}
		Ξ^+	2570	neutral	$\bar{\Xi}^\circ$	10^{-10}
	omega	Ω^-	3290	negative	$\bar{\Omega}^+$	10^{-10}

* Mass of electron is 1 unit on this scale

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Prologue

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Fig. 23.2 Sir P.M.S. Blackett, London.

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P. 73 *Introduction to the detection of nuclear particles in a bubble chamber*, The Ealing Press, Cambridge, Mass.

P. 74 Professor Carl Anderson, California Institute of Technology.

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Pp. 76, 77(all except diagram top right), 79 *Introduction to the detection of nuclear particles in a bubble chamber*, The Ealing Press, Cambridge, Mass.

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Answers to End of Section Questions

Chapter 21

Q1 It was phosphorescent.

Q2 No treatment was needed—the emission was spontaneous.

Q3 Their apparent constancy—they couldn't be turned off or even varied.

Q4 It isn't—although slight differences might be observed because of the other element absorbing some of the radiation.

Q5 The radioactivity was much greater than expected for the amount of uranium in the ore.

Q6 separating it from barium, which is almost identical chemically

Q7 from most to least penetrating: γ, β, α

Q8 β particles were found to have the same q/m ratio as electrons.

Q9 α rays were deflected much less than β rays by a magnetic field.

Q10 Its emission spectrum, when caused to glow by an electric discharge, was the same as helium's.

Q11 It occurs when only a single pure element is present, and isn't affected by chemical combinations of that element.

Q12 The mass of a daughter was found to be less than the mass of the parent by the mass of a helium nucleus.

Q13 1) Many of the substances in a series have the same chemical properties.
2) There are only small percentage differences in atomic mass.
3) Many of the substances decayed very rapidly into something else; all three kinds of rays are given off by the mixture.

Q14 1/16 of it

Q15 No definite prediction is possible. As usual, the odds are 50:50 that one of them will disintegrate. (But the odds are 1 in 4 that both will, and 1 in 4 that neither will.)

Chapter 22

Q1 They were chemically the same as previously known elements.

Q2 decreases 4 units; stays essentially the same

Q3 decreases by 2 + charges; increases by 1 + charge

Q4 by subtracting α particle masses from the mass of the parent of the decay series

Q5 The ions coming out of the "velocity selector" all have the same speed.

Q6 1) faint second line in mass spectrum of pure neon
2) different atomic masses of samples of neon separated by diffusion
3) more intense second line in mass spectrum of one of the samples separated by diffusion

Q7 More massive atoms have a lower average speed and so diffuse more slowly than less massive ones.

Q8 ${}_{78}Pt^{194}$; platinum.

Q9 (A-4)

Q10 (Z+1)

Q11 an isotope of hydrogen with twice the atomic mass of ordinary hydrogen

Q12 The third isotope has a very low abundance.

Q13 ${}_{6}C^{12}$

Chapter 23

Q1 Several atomic masses (which were not recognized as the average of several isotopes) were not close to whole multiples of the atomic mass of hydrogen.

Q2 12 protons and 6 electrons

Q3 In a cloud chamber there was no after-collision track for the α particle.

Q4 The way it knocked protons out of paraffin would be for γ rays a violation of the principles of energy and momentum conservation.

Q5 A neutron has no charge, and so isn't deflected by magnetic or electric fields, nor does it leaves a track in cloud chamber.

Q6 7 protons and 7 neutrons

Q7 a nucleus of 2 protons and 2 neutrons, surrounded by 2 electrons

Q8 A neutron in the nucleus changes into a proton and a β particle, which immediately escapes.

Q9 Without the extra particle, there was no way to explain the disappearance of energy in β-decay.

Q10 The repulsive electric force exerted by the large charge of the heavy nucleus on an α particle prevents it from reaching the nucleus.

Q11 Protons have only a single charge.

Q12 They have no electric charge and so are not repelled by nuclei.

Q13 False: Neutron capture, for example, can produce a heavier isotope of the same element.

Q14 ${}_{14}Si^{28}$

Q15 $_6C^{13}$. 7 protons, 6 neutrons before; 6 protons, 7 neutrons after.

Chapter 24

Q1 No, in some nuclear reactions energy is absorbed.

Q2 It can go off as γ rays or as the KE of the product particles.

Q3 A nuclide with a high *average* binding energy is more stable.

Q4 No. Light nuclei are lower on the curve than heavy nuclei.

Q5 capture of a neutron by a uranium nucleus, then the β decay of the new nucleus

Q6 neutrons

Q7 a substance which slows down neutrons

Q8 It slows down neutrons well (because of the abundance of H atoms), but it also absorbs many (to form "heavy" water).

Q9 The positively charged nuclei repel each other and high speeds are necessary for the nuclei to come near enough in collisions to fuse.

Q10 Since at very high temperatures the gas is ionized, a properly shaped magnetic field could deflect the charged particles away from the walls.

Q11 decreasing

Q12 The protons in a nucleus repel each other with intense electric forces.

Q13 The average binding energy curve suggests that each particle in the nucleus is bound only by its immediate neighbors.

Q14 An excited nucleus becomes distorted in shape; electric repulsion between bulges then forces them apart.

Q15 The excitation energy resulting from neutron capture alone is less than the activation energy required for fission.

Q16 They correspond to completed shells (or sets of energy states) of protons and neutrons in the nucleus.

Q17 Your answer should be that this is not a sensible question. Both models are incomplete; the point is not to decide between them, but to blend them into a more complete general model.

Acknowledgments

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